HEAVY ELECTRICAL ENGINEERING

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THIS BOOK IS DEDICATED TO

ERNST DANIELSON

UNDER WHOSE GUIDANCE AND INFLUENCE THE AUTHOR

ACQUIRED HIS FIRST ENTHUSIASM FOR

ENGINEERING WORK.

PREFACE

Many text books have been published under the general title of "Electrical Engineering." An examination of these books reveals on the part of their authors a conception of the preferential scope of the subject which is at complete variance with my conception. Hence, beyond the similarity of title, there is nothing in common between the present treatise and these others.

I have omitted routine descriptive material as well as the elementary generalities regarding electricity and magnetism, and I have directed my efforts to an attempt to familiarize the reader with various considerations and calculations of which a sound knowledge should be acquired in order to enable him effectively to engage in practical electrical engineering work.

Regrettable as it appears, it is nevertheless a fact that the real progress in electrical engineering is being made by too small a majority of those engaged in the electrical engineering profession. Many have not the remotest approach to broad knowledge of the subject; often they have not the energy or the enterprise to exercise their own reasoning faculties. Such are hardly more than figure-heads desirous on the one hand of being on the side of the most fashionable engineering fad, so soon as there is no longer any doubt of its being fashionable, and on the other hand hesitating to depart from the cut-and-dried practice of years' standing, which makes the preparation of plans a mere matter of copying, and eliminates all risk and uncertainty. Swayed by these opposing tendencies, they soon become incapable of seeing any engineering question in its true aspects. Steam turbines are recommended, utterly regardless of whether condensing facilities are sufficient; single phase traction by commutator motors is heralded with a flourish of trumpets by the very engineers who had previously taken up the position that one of the chief objections to the continuous current motor is the necessity of employing a commutator; electrical

energy is developed from water power and transmitted over considerable distances to a market which could have been supplied at a much lower price by putting down steam-driven plant on favourable sites in the vicinity; enormous sums are sunk in electric power schemes which competent advisers could have demonstrated to be foredoomed to failure; extra-high voltage is used on underground cables when a lower voltage would have been more economical, while, on the other hand, tons of superfluous copper are suspended overhead owing to antiquated prejudices and restrictions limiting the voltage.

One cannot, of course, expect much with industry organized as it at present is, on the basis of sordid competitive motives, and it is probably too much to expect this state of affairs to have other result than to inculcate subserviency in the engineers employed on the staffs of manufacturing companies, and to stimulate the zest with which they enter into the spirit of defeating attempts at sound engineering. For sound engineering can be attempted under a system of competitive tenders only when rigorously sound specifications are issued as a basis for the tenders, and in their struggle for promotion the engineers in manufacturing concerns are apt to cater to the policy which looks no further than the obtaining of immediate orders for their companies, and are rewarded by posts where they are in a position still more effectively to impede sound engineering work.

I shall feel well pleased if this treatise contributes to the exposure of these fundamental fallacies and pernicious tendencies; to the stimulating of rational electro-technical investigations and, in general, to promote electrical engineering progress along sound lines.

Alert and well-trained minds, capable and eager to hold independent views when based on common sense, and not shrinking from the enormous labour associated with genuinely creative engineering work, are, with the broadening field of electrical engineering, urgently needed at the present time. The acquirement of a true engineering instinct is an all-important essential. Behrend states that:—

"There is in the realm of ideas a distinct difference between 'natural' ideas and 'forced' ideas. The natural idea may be likened to a plant growing under favourable conditions and adapting itself to its environment; the forcéd idea may be likened to a plant raised in a hot-house, with the exclusion of such conditions as might have a tendency to prevent its development. The natural idea will

survive; *the forced idea will go to the wall;* but it is only after extended experiments conducted on a large scale have been laboriously completed, that we realize that an idea has been followed out that could have lived only under particularly favourable conditions, such as are not usually found in practical operation."

I am of opinion that were engineers to display greater frankness in dealing with current engineering questions as they arise, there could not fail to result a more general acquirement of true engineering instincts and an avoidance, to a greater extent, of the wasteful method of only distinguishing "forced" ideas after the loss of much valuable time and the waste of vast sums of money.

As a case in point the single phase railway mania may be cited. This has even now hardly run its course, although a thoughtful consideration of the case should have long since enabled engineers to see that it is a "forced" idea. Behrend points out that:

"The very much reduced output of both generators and motors, if operated single phase; the reduced efficiency; the impaired regulation; the increased heating and less stability of single phase motors and generators, connected with the increased cost resulting from the greater amount of material required; these form the main reasons which induce me to call the recent attempts which have been made in the utilization of single phase currents a forced idea. . . . If single phase currents are to be used successfully, a new *creative idea* must be introduced which will do away with some of the disadvantages peculiar to the present single phase apparatus."

Another instance cited by Behrend on this same occasion is so remarkably pertinent that I should like to call attention to it:—

"In the category of the forced ideas is to be placed the idea of transmitting large volumes of power by means of high potential continuous current. That such things can be done is unquestionable, but to do them by means of high potential continuous current is unreasonable. The intuition of the experienced engineer, which is, as it were, the consolidated experience of many years, will guard him against becoming too deeply wrapt up in schemes of this sort."

The means by which the true engineering instinct may best be acquired cannot be concisely set forth. In my opinion, however, one thing is very important, and that is, to be as frank as possible, not only when discussing engineering questions with others, but also, when working with such questions by ourselves; equally important it is, and by no means easy, to be rigorously frank with ourselves and so not to delude ourselves into placing

confidence in premature conclusions. The first-mentioned relation is nowadays but little more than a farcical battle of "bluff," neither participant displaying much sincerity nor crediting others with more. In the second relation, our attitude towards ourselves, there is sometimes scarcely less deception. In an interesting contribution to the *Times Engineering Supplement* for January 8, 1908, Prof. Ayrton relates that Lord Kelvin once, in a spirit of mischief, had printed and sent out to various of his friends copies of a paper containing a number of complicated equations accompanied by wholly meaningless and unintelligible text. The paper was reverentially received, and Lord Kelvin used to relate with a twinkle in his eye that "nobody has yet found any mistake in that paper." We aspire to employ mathematical or other complex methods which most of us are by nature or education utterly incompetent truly to comprehend, and we consider this latter circumstance to be so woefully humiliating that we have not the courage to admit it even to ourselves. Is it not far better, in such a plight, to throw away these complicated and, to us at any rate, useless tools, and turn to simple, if less elegant processes?

It is, however, useless to generalize even in such questions, and when reflecting on these lines, one is apt to come round to the point of view enunciated somewhat as follows by Ruskin :—

"Such, then, are a few of the great principles, by the enforcement of which you may hope to promote the success of the modern students of design; but you should remember that none of these principles will be of any service whatsoever unless you fully recognize that they are in one profound and stern sense, useless. By this I mean that you must understand that neither you nor anyone can, in the great ultimate sense, teach anybody how to make a good design. If designing could be taught, all the world would learn, as all the world reads or calculates. But designing is not to be spelled nor summed. My men continually come to me, in my drawing class in London, thinking I am to teach them what is instantly to enable them to gain their bread. 'Please, sir, show us how to design.' 'Make designers out of us.' And you, I doubt not, partly expect me to tell you to-night how to make designers of your Bradford youths. Alas! I could as soon tell you how to make or manufacture an ear of wheat, as to make a good artist of any kind. I can analyse the wheat very learnedly for you, and tell you that there is starch in it, and carbon, and silex. I can give you starch and charcoal and flint, but you are as far from your ear

of wheat as you were before. All that can possibly be done for anyone who wants ears of wheat, is to show him where to find grains of wheat, and how to sow them, and then, with patience—ground and weather permitting—the ears will come. So in this matter of making artists—first you must find your artist in the grain; then you must plant him; fence and weed the field about him, and with patience—ground and weather permitting—you may get an artist out of him, not otherwise."

If we substitute engineering students for Ruskin's audience of young artists, the pertinence and soundness of the view is very striking.

Before concluding this Preface I wish to acknowledge my indebtedness to the work of the late Prof. Lewicki, and of Mollier, for certain fundamental data relating to the phenomena of friction in steam and of the properties of superheated steam; to Carter's investigations in the subject of electric traction, and to the *Electrical Review*, the *Electrical Times*, the *Times Engineering Supplement*, *Electrical Engineering*, the *Railway Gazette*, and the *Tramway and Railway World*, for the courteous permission to employ certain extracts from the columns of their publications.

Messrs. Edward Arnold and Messrs. Whittaker & Co. have also kindly permitted certain brief extracts to be made from Wilson and Lydall's *Electric Traction*, and from Stevens and Hobart's *Steam Turbine Engineering*.

Had not the preparation of the MS. preceded Lord Kelvin's death, I should, throughout the treatise, have employed the kelvin for the unit of energy, instead of the kw hr, and I earnestly advocate the general use of the term "kelvin" in this sense. To Mr. J. B. Sparks I am indebted for much able technical assistance, particularly in the sections relating to the transmission of electrical energy.

LONDON, 1908. H. M. HOBART.

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HEAVY ELECTRICAL ENGINEERING

CHAPTER I

Introductory

Scope of this Treatise.—Questions concerning the design of apparatus are throughout this treatise regarded as subsidiary to those relating to the design of the stations in which the apparatus is employed. The design of electrical machinery is in itself so broad a subject that a special course of study is necessary for any approach to adequate treatment, and it cannot be considered in the present treatise. In like manner, the design of steam boilers, superheaters, piston engines, steam turbines, gas engines, pumps, condensers, cooling towers, and other apparatus employed at a generating station, constitute equally broad subjects. We shall in the earlier chapters aim to acquire familiarity with the results which can be obtained from the principal amongst these component pieces of apparatus, and to learn to correctly combine them for efficient service in aggregates which we shall denote as generating stations.

Energy.—We are chiefly concerned in this treatise with three forms of energy, namely, heat energy; electrical energy; mechanical energy. When energy manifests itself in the form of heat energy, it is convenient to briefly call it "heat"; when in the form of electrical energy, it may be called "electricity"; finally, when in the form of mechanical energy, it may be called "work".

Unit of Energy.—The quantity of energy when in any of these forms, may be expressed in kilowatt hours (kw hr).

Kilowatt Hour.—The most frequently occurring occasions when we must express energy quantitatively, are those on which it is being transformed from one kind into another, as, for instance, from electricity into heat. The kilowatt hour is 1000 watt hours. The watt hour is the quantity of electricity which is

transformed into heat in a wire of one ohm resistance when a current of one ampere flows through it for one hour. As a potential difference of one volt is required to produce a current of one ampere in a circuit of one ohm resistance, one watt hour is equal to one volt ampere hour for continuous current and for alternating current at unity power factor. It is, however, to be noted that in heavy electrical engineering the watt hour is an inconveniently small quantity, and the kilowatt hour is more convenient, and is thus taken as a unit of energy.

In the following chapters it will appear that even the kilowatt hour is often an inconveniently small unit, for in some departments of heavy electrical engineering, undertakings requiring millions of kilowatt hours per annum are involved.

It has been customary to denote this quantity of electrical energy as one Board of Trade unit since it is a unit which has been officially adopted by the Board of Trade, and it is still frequently expressed in this way. It is, however, more often expressed as one kilowatt hour.

When no ambiguity is thereby introduced, it is often customary to briefly designate this quantity of energy as one "unit"; but this course is not to be recommended, as the word "unit" should be reserved for use in its more general sense.

In this treatise the following terms are used in dealing with quantities of energy:—

1 watt hour . . . (1 w hr)
1 kilowatt hour . . (1 kw hr) = 1000 w hr.

Weight and Volume.—One ton may be defined as the weight of one cubic meter of water at a temperature of 4°.[1]

1 ton = weight of 1 cubic meter (1 cu m) of water
= weight of 1000 cubic decimeters (1000 cu dm) of water
= weight of 1000 liters (1000 l) of water
= 1000 kilograms (1000 kg)
= 1 000 000 grams (1 000 000 g).

Pressure.—The unit of pressure is 1 kilogram per square centimeter.[2] When not otherwise expressly stated, *absolute* pressures

[1] 4° is the temperature of maximum density of water. Throughout this treatise the Centigrade temperature scale is employed, and instead of by four deg. Cent. or 4° C. this temperature is often indicated by 4°.

[2] A pressure of one kilogram per square centimeter is equivalent to the pressure of a mercury column with a height of 735,5 mm. It is almost equivalent to the normal atmospheric pressure. For this reason the unit of pressure is sometimes designated a "metric atmosphere." As a unit, it has the advantage over the ordinary "atmosphere" that it is independent of barometric variations.

are to be understood; that is to say, pressures are referred to an absolute vacuum, and not to atmospheric pressure.

Relation between Heat and Temperature.—The relation between heat and temperature for water and steam may be illustrated by means of the curve in Fig. 1, which represents the occurrences attending the absorption of energy by one ton of water, *i.e.*, the "heating" of one ton of water. During the entire operation the

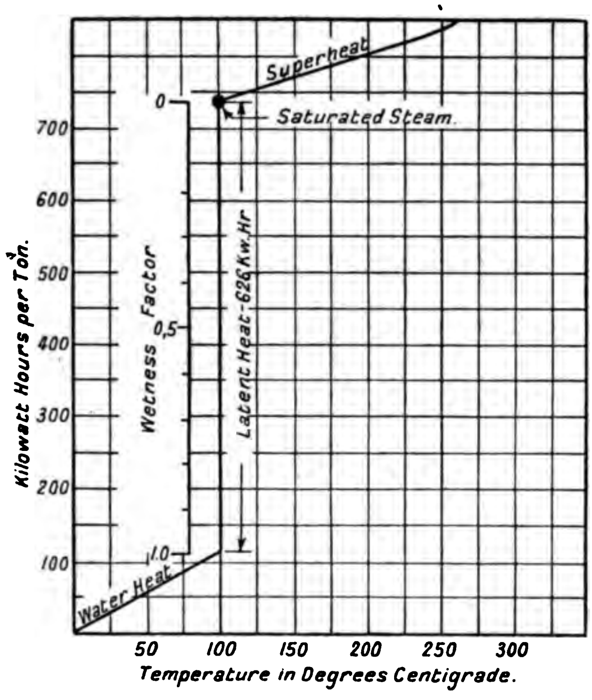


Fig. 1.—Relation between Heat and Temperature for Water and Steam at Atmospheric Pressure.

specific pressure is maintained constant at 1 kg. The curve consists of three distinct portions. The first portion, marked "Water Heat", slopes upward; the second portion, marked "Latent Heat", is vertical; the third portion, which is marked "Superheat", is slightly curved, but its general character is very similar to that of the first portion.

The first portion of the curve represents the heating of water at atmospheric pressure. For all practical purposes the line is

straight, since the rise in temperature is closely proportional to the heat added.

A consideration of the extent of the deviation from a straight line must necessarily be prefaced by a discussion of the "specific heat". The meaning of the term "specific heat" may be illustrated by an example. At 80° 1,172[1] kw hr are required to raise the temperature of one ton of water by 1°. The corresponding amount of energy required to raise by 1° the temperature of one ton of water at 0° is only 1,160 kw hr. The specific heat of water at 80° is obtained by dividing 1,172 by 1,160, and is consequently equal to 1,010. The quantity of energy, 1,160 kw hr, which is absorbed in raising the temperature of one ton of water from 0° to 1°, is the standard of reference as regards specific heat, since water at 0° has been chosen as the standard substance, and its specific heat at that temperature is taken as unity.

The specific heat of any body at any temperature is obtained in the above manner by dividing the kilowatt hours required to cause in a weight of one ton a rise of temperature of 1°, by 1,160, as this is the energy in kilowatt hours required to raise one ton of water at 0°, by 1°.

TABLE I.

The Specific Heat of Water at Various Temperatures.

Temperature in Degs. Cent.	Specific Heat.	Energy in Kilowatt Hours required to raise 1 Ton of Water by 1°.
0	1,000	1,160
20	1,001	1,161
40	1,003	1,163
60	1,006	1,167
80	1,010	1,172
100	1,013	1,175
120	1,018	1,181
140	1,023	1,187
160	1,029	1,193
180	1,036	1,202
200	1,044	1,211

[1] Careful attention should be given to the use of the decimal sign in this treatise. A comma is employed in all cases. Thus; one and thirteen one-hundredths is written 1,13.

In the case of *whole* numbers consisting of four or more integers, a space is left between every three, but no comma is used, thus; one million is written 1 000 000.

The values of the specific heat of water at various temperatures are given in Table I.

When, at atmospheric pressure, a ton of water has been brought to a temperature of 100°, the absorption of additional energy does not cause a further rise in temperature until this additional energy has amounted to 626 kw hr. Consequently the second portion of the curve in Fig. 1 is a vertical line of a length corresponding to 626 kw hr.

The heat thus requiring to be added before any further rise in temperature is occasioned, is called the "latent heat" of the water or the latent heat of vaporisation or of evaporation of water.

The energy corresponding to the latent heat may be divided into two components. The first component represents the energy necessary to change the molecular state, and is termed the internal latent heat; the second component represents the energy required to expand the water against the surrounding pressure, from its liquid volume to its gaseous volume, *i.e.*, to its volume when converted into steam. This component is much smaller than the first component. It is termed the external latent heat, and ranges, according to the specific pressure, from 6 per cent. to 10 per cent. of the total latent heat.

If, instead of atmospheric pressure, other pressures are maintained during the conversion of one ton of water into steam, the latent heat, as well as its two components, have other values. These are given in Table II. for a number of different pressures. In the second column of the table are given the corresponding temperatures at which vaporisation occurs.

TABLE II.

Table of the Internal, the External, and the Total Latent Heat of Vaporisation of Water.

Absolute Pressure in Kg per Sq Cm.	Temperature of Vaporisation in Deg. Cent.	Latent Heat of Vaporisation in Kilowatt Hours per Ton.		
		INTERNAL.	EXTERNAL.	TOTAL.
1	99	579	47	626
2	120	563	49	612
4	143	541	51	592
8	170	518	53	571
12	187	502	54	556
16	200	487	55	542
20	211	475	56	531

Prior to the absorption by the ton of water at vaporisation temperature, of the entire amount of energy corresponding to its latent heat, the ton of water will not have been converted entirely into steam, but will be a mixture of water and steam. At atmospheric pressure the latent heat of one ton of steam is 626 kw hr. When only half of this quantity of energy, *i.e.*, when only 313 kw hr,

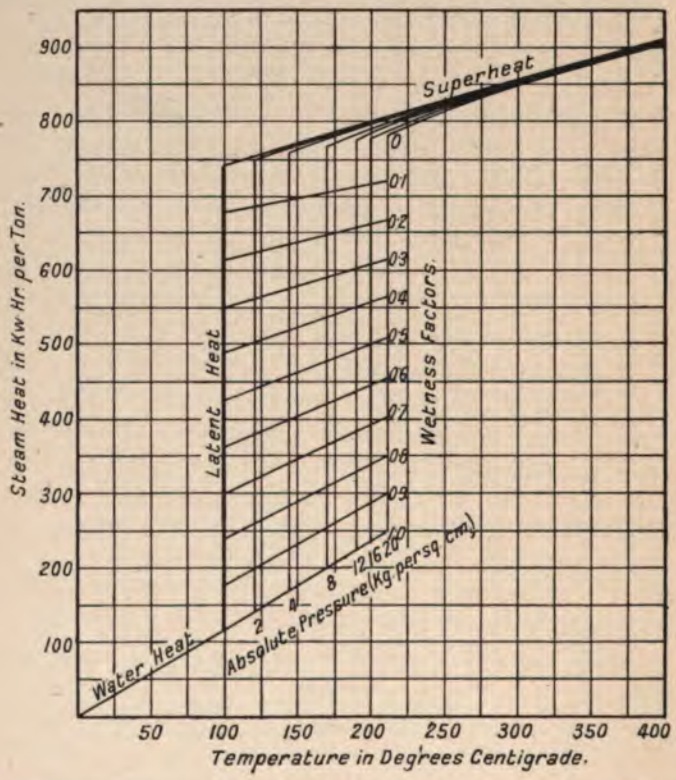


Fig. 2.—Relation between Heat and Temperature for Water and Steam at Various Pressures.

has been absorbed, we shall have a mixture consisting of 0,5 ton of water and 0,5 ton of steam. To the diagram in Fig. 1 has been added a scale showing the "wetness" of the steam at various stages of the process of imparting 626 kw hr to the ton of water. At the commencement of the process the "wetness" is 100 per cent., or we may say that the steam has a wetness factor of 1,00. When 125 kw hr have been absorbed the wetness factor is 0,80, and when

the entire 626 kw hr have been absorbed the wetness factor is 0,00, and we have so-called " saturated " steam.

Further additions of heat are accompanied by increase of temperature, and the steam is said to be " superheated ". This part of the process corresponds to the right-hand sloping portion of the diagram in Fig. 1. The angle at which this portion of the diagram slopes upward is dependent upon the specific heat of superheated steam.

The specific heat of superheated steam varies considerably with the temperature and pressure. In Table VI. and Fig. 3 the at present most probable values are given. Physicists are occupied in obtaining more reliable data. For our purposes at the moment it is sufficient to state that the specific heat of steam is roughly about half of that of water. Hence a given quantity of energy imparted to a ton of steam will raise its temperature through about twice as many degrees as the same amount of energy imparted to one ton of water.

These data are embodied in the diagrams in Fig. 2, where are drawn for various pressures, a set of lines corresponding to those already given for an absolute pressure of 1 kg per sq cm in Fig. 1.

The leading properties of steam are entered up in Tables III., IV. and V. At the present time, considerable difference of opinion exists amongst physicists with regard to the values of the specific heat of superheated steam at various temperatures and pressures. The values employed in the construction of Tables III. to V. are in accord with those given by Mollier in his brochure entitled " Neue Tabellen und Diagramme für Wasserdampf "[1].

Mollier's values for the specific heat of steam are given in Table VI. The values given in this Table represent the average specific heat while the temperature of the steam is raised from the temperature of vaporisation to various final temperatures (100°, 150°, 200°, etc.). From these values the curves in Fig. 3 have been drawn.

The specific heat and specific gravity[2] of some common materials are given, together with the kw hr per ton per deg. cent. temperature rise, in Table VII.

Examples of the amount of energy represented by 1 kw hr :—

1. 1 kw hr is sufficient to lift one ton through a height of 367 meters.

[1] Published (1906) by Julius Springer, Berlin.

[2] The specific gravity of a body may be defined as the density, or specific weight of the body in grams per cubic centimeter, kilograms per cubic decimeter, or tons per cubic meter.

TABLE III.

Table of the Energy, in Kilowatt Hours, required to convert One Ton of Water at 0° C. into Steam at Various Pressures and Superheats.

Absolute Pressure in Kg per Sq Cm	Temperature of Vaporisation in Deg. Cent.	Heat in Kilowatt Hours per Ton.								
		Component Parts.					Total Steam Heat.			
		Water Heat.	Latent Heat.	50° C. Superheat.	100° C. Superheat.	150° C. Superheat.	Saturated Steam.	Steam Superheated 50° C.	Steam Superheated 100° C.	Steam Superheated 150° C.
A	B	C	D	E	F	G	H	K	L	M
0,02	17	20	680	28	55	83	700	728	755	783
0,04	29	32	670	"	"	"	704	732	759	787
0,06	36	42	667	"	"	"	709	737	764	792
0,08	41	48	665	"	"	"	713	741	768	796
0,10	46	53	663	"	"	"	716	744	771	799
0,12	49	57	660	"	56	84	717	745	773	801
0,15	54	63	657	"	"	"	720	748	776	804
0,20	60	70	654	"	"	"	724	752	780	808
0,25	65	75	650	"	"	85	725	753	781	810
0,30	69	80	647	"	"	"	727	755	783	812
0,35	72	84	645	"	"	"	729	757	785	814
0,40	76	88	642	"	"	"	730	758	786	815
0,50	81	94	639	"	"	"	733	761	789	818
0,60	86	100	636	"	"	"	736	764	792	821
0,70	90	104	633	29	57	86	737	766	794	823
0,80	93	109	630	"	"	"	739	768	796	825
0,90	96	112	628	"	"	"	740	769	797	826
1,0	99	115	626	"	"	87	741	770	798	828
1,1	102	118	625	"	"	"	743	772	800	830
1,2	104	120	623	"	"	"	745	774	802	832
1,4	109	127	619	30	58	88	746	776	804	834
1,6	113	132	616	"	"	"	748	778	806	836
1,8	116	136	614	"	"	"	750	780	808	838
2,0	120	140	612	"	"	"	752	782	810	840
2,5	127	148	606	"	59	89	754	784	813	843
3,0	133	155	601	"	"	"	756	786	815	845
3,5	138	162	596	"	"	"	758	788	817	847
4,0	143	167	592	31	60	90	759	790	819	849
4,5	147	172	589	"	"	"	761	792	821	851
5,0	151	177	587	"	61	"	764	795	825	854
5,5	155	182	584	"	"	91	766	797	827	857
6,0	158	186	581	"	"	"	767	798	828	858
6,5	161	189	578	32	62	92	767	799	829	859
7,0	164	193	575	"	"	"	768	800	830	860
7,5	167	196	573	"	"	"	769	801	831	861
8,0	170	199	571	"	"	"	770	802	832	862
8,5	172	202	569	"	"	"	771	803	833	863
9,0	174	205	566	33	63	93	771	804	834	864
9,5	177	208	564	"	"	"	772	805	835	865
10	179	211	562	"	"	"	773	806	836	866
11	183	216	559	"	"	"	775	808	838	868
12	187	220	556	"	64	94	776	809	840	870
13	191	225	552	"	65	95	777	810	842	872
14	194	229	549	"	"	96	778	811	843	874
15	197	233	545	34	66	97	778	812	844	875
16	200	237	542	"	"	"	779	813	845	876
18	206	244	536	35	67	98	780	815	847	878
20	211	250	531	"	68	99	781	816	849	880

TABLE IV.

Table of Specific Volume and Specific Weight of Saturated and Superheated Steam.

Absolute Pressure in Kg per Sq Cm	Temperature of Vaporisation in Deg. Cent.	Specific Volume in Cu m per Kg				Specific Weight in Kg per Cu m			
		Saturated Steam.	Steam Superheated 50° C	Steam Superheated 100° C	Steam Superheated 150° C	Saturated Steam.	Steam Superheated 50° C	Steam Superheated 100° C	Steam Superheated 150° C
A	B	N	O	P	Q	R	S	T	U
0,02	17	68	81	93	105	0,015	0,012	0,011	0,010
0,04	29	35	42	48	54	0,028	0,024	0,021	0,019
0,06	36	24	28	32	36	0,042	0,036	0,031	0,028
0,08	41	18	21	24	27	0,055	0,047	0,041	0,037
0,10	46	15	17	20	22	0,066	0,058	0,051	0,046
0,12	49	12	15	17	19	0,081	0,069	0,061	0,054
0,15	54	10	12	13	15	0,100	0,085	0,075	0,067
0,20	60	8	9	10	11	0,130	0,112	0,099	0,089
0,25	65	6,4	7,3	8,3	9,2	0,16	0,14	0,12	0,11
0,30	69	5,3	6,1	6,9	7,7	0,19	0,16	0,14	0,13
0,35	72	4,6	5,3	6,0	6,6	0,22	0,19	0,17	0,15
0,40	76	4,0	4,6	5,3	5,9	0,25	0,22	0,19	0,17
0,50	81	3,3	3,8	4,3	4,7	0,31	0,26	0,24	0,21
0,60	86	2,8	3,2	3,6	4,0	0,36	0,31	0,28	0,25
0,70	90	2,4	2,8	3,1	3,4	0,42	0,36	0,32	0,29
0,80	93	2,1	2,4	2,7	3,0	0,48	0,41	0,37	0,33
0,90	96	1,9	2,2	2,4	2,7	0,53	0,46	0,41	0,37
1,0	99	1,7	2,0	2,2	2,4	0,59	0,51	0,45	0,41
1,1	102	1,6	1,8	2,0	2,2	0,64	0,56	0,50	0,45
1,2	104	1,4	1,7	1,9	2,1	0,70	0,60	0,54	0,49
1,4	109	1,2	1,4	1,6	1,8	0,80	0,70	0,63	0,57
1,6	113	1,1	1,3	1,4	1,6	0,92	0,79	0,71	0,64
1,8	116	1,0	1,1	1,3	1,4	1,02	0,89	0,80	0,71
2,0	120	0,89	1,02	1,14	1,26	1,1	1,0	0,9	0,8
2,5	127	0,72	0,83	0,93	1,02	1,4	1,2	1,1	1,0
3,0	133	0,61	0,70	0,78	0,86	1,6	1,4	1,3	1,2
3,5	138	0,52	0,60	0,68	0,74	1,9	1,7	1,5	1,4
4,0	143	0,46	0,53	0,59	0,67	2,2	1,9	1,7	1,5
4,5	147	0,43	0,47	0,53	0,58	2,4	2,1	1,9	1,7
5,0	151	0,37	0,43	0,47	0,52	2,7	2,3	2,1	1,9
5,5	155	0,34	0,39	0,44	0,48	2,9	2,5	2,3	2,1
6,0	158	0,32	0,36	0,40	0,44	3,2	2,8	2,5	2,3
6,5	161	0,29	0,34	0,37	0,41	3,4	3,0	2,7	2,5
7,0	164	0,27	0,31	0,35	0,38	3,7	3,2	2,9	2,6
7,5	167	0,26	0,29	0,32	0,35	3,9	3,4	3,1	2,8
8,0	170	0,24	0,28	0,30	0,33	4,1	3,5	3,3	3,0
8,5	172	0,23	0,26	0,29	0,31	4,4	3,8	3,5	3,2
9,0	174	0,22	0,24	0,27	0,30	4,6	4,1	3,7	3,4
9,5	177	0,21	0,23	0,26	0,28	4,9	4,3	3,9	3,6
10	179	0,20	0,22	0,24	0,27	5,1	4,6	4,1	3,8
11	183	0,18	0,20	0,22	0,24	5,6	5,0	4,5	4,1
12	187	0,16	0,18	0,20	0,22	6,1	5,4	4,9	4,5
13	191	0,15	0,17	0,19	0,21	6,5	5,9	5,3	4,8
14	194	0,14	0,16	0,18	0,19	7,0	6,4	5,7	5,2
15	197	0,13	0,15	0,16	0,18	7,5	6,8	6,1	5,6
16	200	0,11	0,14	0,15	0,17	7,9	7,3	6,6	6,0
18	206	0,11	0,12	0,14	0,15	8,9	8,2	7,4	6,8
20	211	0,10	0,11	0,13	0,14	9,6	8,9	8,1	7,5

TABLE V.

Table of the energy in Kilowatt Hours required to convert One Ton of Water at 0° C into Steam at various Temperatures and Pressures.

Absolute Pressure in Kg per Sq Cm	Temperature of Vaporisation in Deg. Cent.	Steam Heat of Saturated Steam in Kilowatt Hours per Ton.	Steam Heat (in Kilowatt Hours per Ton) of Steam superheated to following Final Temperatures in Degrees Centigrade.							
			100°	150°	200°	250°	300°	350°	400°	450°
A	B	C	D	E	F	G	H	K	L	M
0,02	17	700	747	775	803	831	859	885	913	940
0,04	29	704	"	"	"	"	"	"	"	"
0,06	36	709	"	"	"	"	"	"	"	"
0,08	41	713	"	"	"	"	"	"	"	"
0,10	46	716	746	774	802	830	858	884	912	"
0,12	49	717	"	"	"	"	"	"	"	"
0,15	54	720	"	"	"	"	"	"	"	"
0,20	60	724	"	773	"	"	"	"	"	"
0,25	65	725	745	"	801	824	"	"	"	"
0,30	69	727	"	"	"	"	"	"	"	"
0,35	72	729	"	"	"	"	"	"	"	"
0,40	76	730	"	"	"	"	"	"	"	"
0,50	81	733	744	772	800	828	857	883	911	939
0,60	86	736	"	"	"	"	"	"	"	"
0,70	90	737	"	"	"	"	856	"	"	"
0,80	93	739	"	771	"	827	"	"	"	"
0,90	96	740	"	"	"	"	"	"	"	"
1,0	99	741	742	770	799	826	855	882	"	938
1,1	102	743		"	"	"	"	"	"	"
1,2	104	745		"	"	"	"	"	"	"
1,4	109	746		"	"	"	"	"	"	"
1,6	113	748		"	"	"	"	"	"	"
1,8	116	750		"	"	"	"	"	"	"
2,0	120	752		769	798	"	854	"	"	"
2,5	127	754		768	797	"	"	881	"	"
3,0	133	756		767	796	825	853	"	"	"
3,5	138	758		766	795	"	"	880	"	"
4,0	143	759		764	794	824	852	879	910	"
4,5	147	761			"	"	"	"	"	"
5,0	151	764			"	"	"	"	"	"
5,5	155	766			"	"	"	"	"	"
6,0	158	767			793	823	"	"	"	"
6,5	161	767			792	822	"	"	909	"
7,0	164	768			791	"	851	"	"	"
7,5	167	769			790	821	"	"	"	"
8,0	170	770			789	820	850	879	908	937
8,5	172	771			"	"	"	"	"	"
9,0	174	771			798	"	"	"	"	"
9,5	177	772			"	"	"	"	"	"
10	179	773	Wet Steam.		787	819	849	878	"	936
11	183	775			786	"	"	"	"	"
12	187	776			785	818	848	"	907	"
13	191	777			784	817	"	"	"	"
14	194	778			782	816	847	877	"	"
15	197	778			781	815	846	"	906	"
16	200	779			779	813	845	876	905	935
18	206	780				812	844	"	"	"
20	211	781				811	843	815	905	"

TABLE VI.

Table of the Average Specific Heat of Steam, heated from the Temperature of Vaporisation to Various Final Temperatures.

Absolute Pressure in Kg. per Sq. Cm.		0,1	0,5	1	2	4	6	8	10	12	14	16
Temperature of Vaporisation in ° C.		46	81	99	120	143	158	170	179	187	194	200
Final Temperature of Steam in ° C.	100	0,480	0,490	0,501								
	150	0,479	0,488	0,495	0,513	0,533						
	200	"	0,486	0,491	0,505	0,523	0,538	0,558	0,573	0,588	0,601	
	250	"	0,484	0,489	0,500	0,514	0,528	0,543	0,556	0,569	0,578	0,588
	300	"	0,483	0,487	0,496	0,508	0,519	0,531	0,541	0,551	0,562	0,569
	350	"	0,482	0,485	0,493	0,503	0,513	0,522	0,531	0,539	0,547	0,555
	400	0,478	"	0,484	0,491	0,500	0,508	0,517	0,523	0,531	0,538	0,545
	450	"	"	0,483	0,489	0,497	0,505	0,513	0,519	0,525	0,531	0,537

TABLE VII.

Table of Specific Gravity and Specific Heat of Various Materials.

Material.	Specific Gravity (Tons per cu m)	Specific Heat.	Kilowatt Hours required to raise the Temperature of 1 Ton by 1°.	Kilowatt Hours required to raise the Temperature of 1 Cubic Meter by 1°.
Water ...	1,0	1,0	1,16	1,16
Ice	0,93	0,49	0,57	0,53
Coal	1,3	0,24	0,28	0,36
Wrought Iron	7,7	0,11	0,13	1,00
Cast Iron ...	7,2	0,13	0,15	1,08
Copper ...	8,9	0,10	0,12	1,07
Lead	11,4	0,03	0,035	0,40
Zinc	6,9	0,09	0,11	0,76
Aluminium ...	2,6	0,22	0,25	0,65
Transformer Oil... ...	0,9	0,75	0,87	0,78

2. 1 kw hr is consumed at the trolley in propelling a 10-ton tramcar of good design on a good and level track for a distance of from 1 to 2 kilometers or thereabouts (according to the number of stops per kilometer), at a schedule speed of some 12 kilometers per hour.

3. 1 kw hr is absorbed in 84 hours by a 12-candle power lamp requiring 1 watt per candle power. If the lamp is only in circuit for an average period of two hours per day, 8,7 kw hr will be absorbed by the lamp in the course of one year, provided

that it survives for 730 hours in circuit, with an average efficiency of 1 watt per candle power and that its candle power does not alter.

If the charge is 3*d*. per kw hr (*i.e.*, per "unit"), the cost of energy for this lamp will amount to $\left(\frac{730}{84} \times 3 = \right)$ 26*d* for the year.

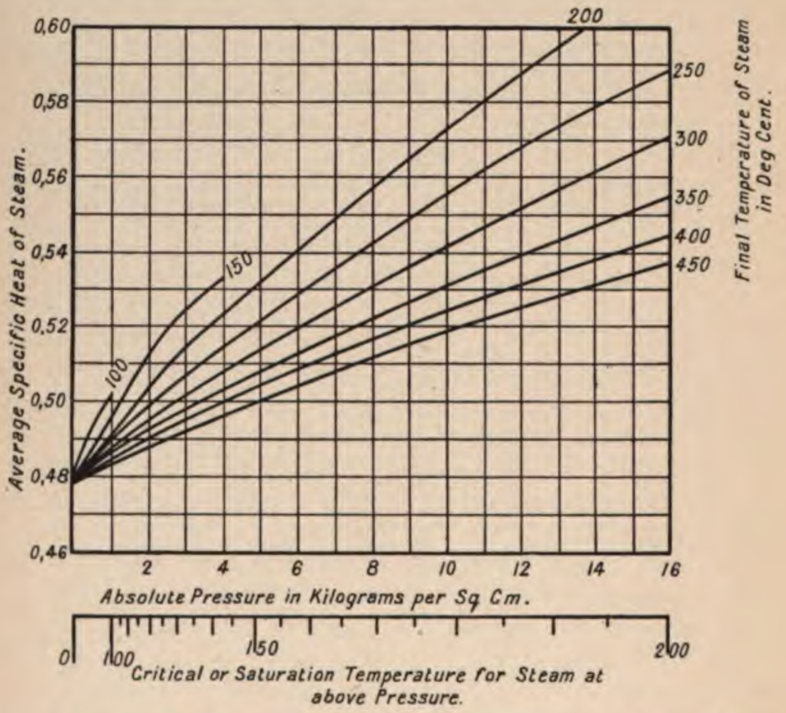


Fig. 3.—Curve showing the Average Specific Heat for Steam Superheated from the Saturation Temperature to various Higher Temperatures. (Note.—The above Curves are plotted from results given by Mollier.)

Replacing the lamp once per year, at a cost of 30*d*, brings the total annual outlay per lamp to

$$26 + 30 = 56d.$$

To this must also be added an equitable proportion of the meter rental. On these assumptions, the lamp thus costs a matter of some 5 shillings per year.

4. The latent heat of liquefaction of ice is 93 kw hr per ton;

that is to say, to convert one ton of ice at 0° into one ton of water at 0° requires the absorption of 93 kw hr.

5. The specific heat of ice is 0,49. Consequently to convert one ton of ice at $-$ 8° into water at 0° requires the application of 97,6 kw hr, this amount being accounted for as follows:

4,6 kw hr are required to raise the temperature of the ice to 0°, and 93 kw hr are required to liquefy the ice.

6. To convert one ton of ice at $-$ 8° into water at + 8° requires the expenditure of 107 kw hr, this amount being accounted for as follows: as in example (5), 97,6 kw hr are required to change the ice into water at 0°, and a further 9,3 kw hr to raise the temperature of the water to 8°.

7. The average specific heat of transformer oil is 0,75, of copper 0,10, of iron 0,11. In a certain transformer, the weight of the copper is 100 kg, the laminations 200 kg, the cast iron case 150 kg, and the oil 180 kg. The internal loss amounts to 1 kw, and it is required to find the time required to cause a rise of temperature of 40°, assuming that the heat is exclusively employed in causing a rise of temperature, and that none is radiated from the external surface of the frame.

The oil requires $0,75 \times 1,16 \times 0,18 \times 40 = 6,3$ kw hr. Similarly, the copper requires 0,46 kw hr, the laminations 1,02 kw hr, and the frame 0,75 kw hr The total heat required is 8,5 kw hr, so that if the losses in the transformer are 1 kw, the time would be 8,5 hours, under the conditions set forth.

Energy Transformations.—Electrical energy—or briefly—electricity, can be transformed into work energy—or work, with an efficiency as high as 95 per cent. in large motors. Work may be transformed into electricity with equally high efficiency. The remaining 5 per cent. or thereabouts, is converted into heat energy or—briefly—into heat. Electricity and work may both be converted into heat with an efficiency of 100 per cent. Thus, if an electric current is sent through a resistance, the electrical energy may be entirely converted into heat in the resistance. If work is performed in stirring water, as in Joule's experiment, the work energy may be entirely transformed into heat energy. The so-called "generation" of electrical energy in generating stations should, strictly speaking, be described as the *transformation* of energy from heat to electricity.

When we wish to convert heat into electricity or into work, no such high efficiencies are attainable. There are no known means of

transforming heat directly into electricity on a large commercial scale. Heat may, with a low efficiency, be transformed into work in a steam engine or a gas engine, and the work may, at high efficiency, be transformed into electricity. The large portion which, in the first step, is not transformed into work, remains heat; the small part which, in the second step, is not transformed into electricity, is converted into (or *lost* as) heat. Of the heat absorbed by a large steam engine or steam turbine, during the passage of the steam, only some 60 per cent. can, in the present state of the art, ultimately be converted into electricity.

When we trace the process back to the calorific contents of the fuel, it may be stated that it is rarely practicable to convert more than some 8,0 per cent. into electricity. With gas engines some 25 per cent. of the calorific value of the fuel may be transformed into electricity in the circuits supplied from the dynamo driven by the gas engine. The greater efficiency of the gas engine is, however, in large units, offset by the greater cost, greater depreciation and greater space required, as also in many cases by the disadvantage of its less uniform turning moment and its less reliability at its present stage of development.

Let us therefore direct our attention to the steam engine or steam turbine, which, as already stated, permits, in large sets, of converting into electrical energy some 60 per cent. of the energy abstracted from the steam in its passage through the engine. In accordance with this definition of the efficiency of an engine, the heat rejected to the condenser is not regarded as a loss. It may be for instance, and often is, employed in heating processes. Waste heat engines have also been devised for employing the lower temperature ranges. Whether or not it is expedient to further employ the heat energy rejected to the condenser, it is nevertheless heat energy. Subtracting this energy from that contained in the steam at admission, we have as remainder, the energy which has undergone transformation in the steam engine or turbine. A large proportion of this becomes converted from heat energy into useful work energy, and the remainder is ultimately wasted in heating the engine and the surroundings.

The ratio of the energy delivered from the engine as work, to the energy which has been absorbed in the engine, *i.e.*, to the "convertible energy", is designated the "thermodynamic" efficiency. In Table VIII. are set out the amounts of "convertible" energy per ton of steam when working between various admission

TABLE VIII.

Heat, in Kilowatt Hours rendered available for Conversion into Work by the expansion of One Ton of Steam.

Note.—The Values for Steam Initially Saturated are set in heavier Type.

Exhaust Pressure in Kg per Sq Cm.	Admission Pressure in Kg per Sq Cm.																						
	16			14				12				10				8				6			
	Admission Temperature in Degrees Centigrade.																						
	200	250	300	**194**	200	250	300	**187**	200	250	300	**179**	200	250	300	**170**	200	250	300	**158**	200	250	300
0,05	**228**	243	261	**225**	226	241	256	**219**	223	236	250	**211**	217	230	242	**202**	209	222	234	**191**	200	212	226
0,1	**210**	224	240	**205**	208	220	238	**199**	204	215	238	**190**	197	208	222	**180**	188	199	214	**170**	179	190	203
0,2	**188**	200	214	**183**	185	197	210	**176**	179	190	204	**168**	174	182	197	**158**	165	174	187	**146**	154	163	177
0,4	**162**	175	188	**158**	154	172	183	**151**	153	165	176	**144**	148	157	169	**133**	139	148	160	**122**	129	137	150
0,6	**148**	160	173	**113**	144	155	168	**137**	139	150	161	**127**	132	142	153	**118**	123	132	143	**105**	112	121	132
0,8	**138**	147	160	**132**	132	144	154	**125**	128	138	147	**117**	120	130	140	**107**	111	120	130	**95**	100	108	120
1,0	**128**	139	152	**123**	123	134	146	**116**	119	128	128	**108**	112	120	130	**97**	102	110	119	**85**	90	99	109
1,5	**114**	122	133	**106**	108	118	128	**100**	102	111	120	**91**	94	102	111	**80**	83	92	101	**67**	72	79	90

Heat energy (in Kilowatt Hours per Ton) available for Conversion into Work.

TABLE IX.

Wetness Factors at Exhaust, for Steam Expanded Adiabatically from Various Initial Temperatures and Pressures.

Note.—The Values for Steam Initially Saturated are set in heavier Type.

Exhaust Pressure in Kg per Sq Cm.	Admission Pressure in Kg per Sq Cm.																						
	16			14				12				10				8				6			
	Admission Temperature in Degrees Centigrade.																						
	200	250	300	**174**	200	250	300	**187**	200	250	300	**179**	200	250	300	**170**	200	250	300	**158**	200	250	300
0,05	**0,24**	0,21	0,19	**0,23**	0,23	0,21	0,18	**0,23**	0,22	0,20	0,17	**0,22**	0,20	0,18	0,16	**0,22**	0,20	0,18	0,15	**0,20**	0,18	0,15	0,13
0,1	**0,23**	0,20	0,17	**0,22**	0,22	0,19	0,16	**0,22**	0,21	0,18	0,15	**0,21**	0,19	0,16	0,14	**0,20**	0,18	0,14	0,13	**0,18**	0,16	0,13	0,10
0,2	**0,21**	0,17	0,14	**0,19**	0,19	0,16	0,13	**0,19**	0,18	0,15	0,12	**0,18**	0,17	0,14	0,11	**0,17**	0,15	0,12	0,09	**0,16**	0,13	0,10	0,07
0,4	**0,18**	0,14	0,11	**0,16**	0,16	0,13	0,10	**0,16**	0,15	0,12	0,09	**0,15**	0,14	0,10	0,08	**0,14**	0,12	0,09	0,06	**0,12**	0,10	0,07	0,04
0,6	**0,17**	0,13	0,09	**0,15**	0,15	0,11	0,38	**0,15**	0,13	0,10	0,07	**0,14**	0,12	0,09	0,06	**0,13**	0,11	0,08	0,04	**0,11**	0,09	0,05	0,01
0,8	**0,16**	0,12	0,08	**0,13**	0,13	0,10	0,07	**0,14**	0,12	0,09	0,06	**0,13**	0,11	0,08	0,04	**0,11**	0,09	0,06	0,03	**0,10**	0,07	0,04	
1,0	**0,14**	0,10	0,07	**0,12**	0,12	0,09	0,06	**0,12**	0,11	0,08	0,04	**0,12**	0,10	0,07	0,03	**0,10**	0,08	0,04	0,02	**0,09**	0,06	0,02	
1,5	**0,11**	0,08	0,05	**0,11**	0,11	0,07	0,04	**0,10**	0,09	0,06	0,03	**0,09**	0,08	0,04	0,01	**0,08**	0,06	0,03		**0,07**	0,04		

Wetness Factors.

TABLE IX.

Wetness Factors at Exhaust, for Steam Expanded Adiabatically from Various Initial Temperatures and Pressures.

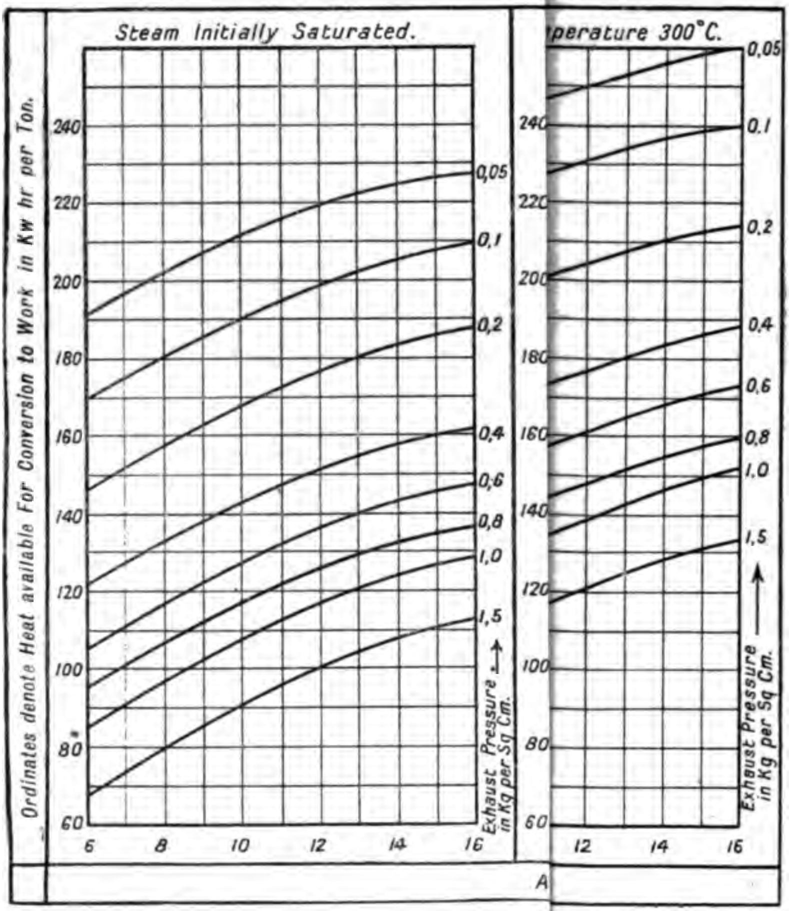
Note.—The Values for Steam Initially Saturated are set in heavier Type.

Exhaust Pressure in Kg per Sq Cm.	Admission Pressure in Kg per Sq Cm. 16			14				12			
	Admission Temperature in Degrees Centigrade.										
	200	250	300	**174**	200	250	300	**187**	200	250	300
0,05	**0,24**	0,21	0,19	**0,23**	0,23	0,21	0,18	**0,23**	0,22	0,20	0,17
0,1	**0,23**	0,20	0,17	**0,22**	0,22	0,19	0,16	**0,22**	0,21	0,18	0,15
0,2	**0,21**	0,17	0,14	**0,19**	0,19	0,16	0,13	**0,19**	0,18	0,15	0,12
0,4	**0,18**	0,14	0,11	**0,16**	0,16	0,13	0,10	**0,16**	0,15	0,12	0,09
0,6	**0,17**	0,13	0,09	**0,15**	0,15	0,11	0,38	**0,15**	0,13	0,10	0,07
0,8	**0,16**	0,12	0,08	**0,13**	0,13	0,10	0,07	**0,14**	0,12	0,09	0,06
1,0	**0,14**	0,10	0,07	**0,12**	0,12	0,09	0,06	**0,12**	0,11	0,08	0,04
1,5	**0,11**	0,08	0,05	**0,11**	0,11	0,07	0,04	**0,10**	0,09	0,06	0,03

Exhaust Pressure in Kg per Sq Cm.	Admission Pressure in Kg per Sq Cm. 10				8				6			
	Admission Temperature in Degrees Centigrade.											
	179	200	250	300	**170**	200	250	300	**158**	200	250	300
0,05	**0,22**	0,20	0,18	0,16	**0,22**	0,20	0,18	0,15	**0,20**	0,18	0,15	0,13
0,1	**0,21**	0,19	0,16	0,14	**0,20**	0,18	0,14	0,13	**0,18**	0,16	0,13	0,10
0,2	**0,18**	0,17	0,14	0,11	**0,17**	0,15	0,12	0,09	**0,16**	0,13	0,10	0,07
0,4	**0,15**	0,14	0,10	0,08	**0,14**	0,12	0,09	0,06	**0,12**	0,10	0,07	0,04
0,6	**0,14**	0,12	0,09	0,06	**0,13**	0,11	0,08	0,04	**0,11**	0,09	0,05	0,01
0,8	**0,13**	0,11	0,08	0,04	**0,11**	0,09	0,06	0,03	**0,10**	0,07	0,04	
1,0	**0,12**	0,10	0,07	0,03	**0,10**	0,08	0,04	0,02	**0,09**	0,06	0,02	
1,5	**0,09**	0,08	0,04	0,01	**0,08**	0,06	0,03		**0,07**	0,04		

Wetness Factors.

PLATE I.



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pressures and temperatures and various exhaust pressures. With an engine of 60 per cent. "thermodynamic" efficiency, the work energy obtained per ton of steam is equal to 0,60 of the "convertible" energy set forth in the table.

The values set forth in the table have been deduced on the assumption of expansion without loss or gain of energy by the steam. Its temperature during this process of so-called "adiabatic" expansion, decreases in accordance with definite thermodynamic laws into which it is not proposed to enter. Accompanying the decrease in temperature, there is, for certain ranges, a condensation of a portion of the steam. The corresponding "wetness factors" are set forth in Table IX.

The data in Table VIII. are plotted in the curves of Figs. 4—7.

CHAPTER II

THE OVERALL EFFICIENCY OF GENERATING STATIONS AND THE RELATION BETWEEN COAL CONSUMPTION AND OUTGOING ELECTRICAL ENERGY

In employing the customary expression "Generating Station" we must clearly recognise that a more exact expression would be "Transforming Station," since in such a station we transform a small part of the energy of combustion of the coal, or other fuel, into electrical energy, at the same time—unwillingly—transforming a much larger part of the energy of combustion of the coal into irrecoverable heat energy. We shall first ascertain how great a percentage of the energy of combustion of coal, engineers have learned to transform into electrical energy.

The Calorific Values of Fuels.—Various kinds of coal contain widely different amounts of stored-up energy per ton. The heat energy obtained by burning one ton of coal in the presence of an ample supply of air and under other suitable conditions, may be expressed as the energy of combustion per ton, or the calorific value per ton.

In Table X. are given representative conservative values for the

TABLE X.

Calorific Values of a Number of Varieties of Coal.

Source.	Nature.	Calorific Value of Coal in Kilowatt Hours per Ton.
Wales	Almost pure anthracite	9800
England	Bituminous	9000
Scotland	Bituminous	8300
United States of America	Anthracite	9000
	Bituminous	8700
Germany ...	Anthracite	8300
	Bituminous	8100
	"Braunkohle" (hard lignite)	6300
	"Braunkohle" (soft lignite)	4300

energy of combustion of various coals, in kilowatt-hours per ton of coal.

We see from Table X. that the available qualities of coal, range in calorific value from 9800 kw hr per ton downwards.[1] 8700 kw hr per ton is a readily obtainable value. This value represents the heat energy obtained by burning one ton of good bituminous coal in the presence of a suitable supply of air, and under otherwise suitable conditions.

Examples of the Amount of Energy contained in One Ton of Coal of a Calorific Value of 8700 *kw hr per ton.*—(1.) Could we transform this heat energy at 100 per cent. efficiency, into electrical energy of suitable voltage, we could run sixty-two 16 c.p. incandescent lamps for one year with the energy yielded by the combustion of one ton of coal.[2] Owing to the losses in transformation, we rarely obtain from one ton of coal sufficient electrical energy for more than four lamp years.

(2.) As another example of the energy contained in a ton of coal with a calorific value of 8700 kw hr, we may say that this energy is sufficient to lift a weight of one ton through a height of about 3200 km; or 3200 tons through one kilometer.

(3.) A further instance of the amount of energy contained in a ton of coal of a calorific value of 8700 kw hr, may be found in the statement that it is about equal to the amount of energy consumed by an ordinary urban tramcar of 12 tons weight, in traversing 10 000 km of average urban route at a schedule speed of 10 km per hour and with three stops (of five seconds duration each) per km, the equipment comprising ordinary continuous current series wound motors with series parallel control, and the tramcar

[1] For the convenience of readers who may still be accustomed to deal with calorific values in British units we may state that 1 kw hr = 3411 British thermal units, and 10 000 kw hr per ton = 15 500 British thermal units per lb.

The plan employed in the present treatise is to express all energy in kilowatt hours, so that the energy, whether in the coal, in the steam or in the electrical system, shall in all cases be expressed in the same unit.

[2] This statement is based on an incandescent lamp consuming 1 watt per candle power.

∴ 1 candle power hour requires 1 watt hour. If the watt hours per ton of coal = 8 700 000 then the candle power hours per ton of coal =

$$\frac{8\ 700\ 000}{1{,}0} = 8\ 700\ 000$$

$$\text{Total candle power} = \frac{8\ 700\ 000}{365 \times 24} = 990$$

$$\text{No. of 16 c.p. lamps} = \frac{990}{16} = 62$$

being accelerated and braked in accordance with present approved practice. That in actual practice, a ton of coal is consumed at the generating station for every 800 car km or less, is due to the fact that some 92 per cent. to 95 per cent. of the energy of combustion of the coal, is transformed into irrecoverable heat energy in the course of the various transformations of energy occurring between the coal pile and the trolley wheel.

(4.) As another example, let us take a 200 ton train, travelling on a level track at a uniform speed of 60 km per hour, and requiring a tractive force of 3 kg per ton. Suppose the locomotive has an efficiency from coal to axles, of 1,5 per cent. for this speed and tractive force. How many kilometers can the train travel while burning one ton of coal, having a calorific value of 8700 kw hr per ton?

Energy transmitted to axles per ton of coal burned =

$$0{,}015 \times 8700 = 130 \text{ kw hr}$$
$$1 \text{ kw hr} = 0{,}367 \text{ ton km}$$
$$130 \text{ kw hr} = 47{,}6 \text{ ton km}$$

Or, a 200 ton train could be lifted through $\frac{47{,}6}{200} = 0{,}238$ km. As the coefficient of friction is 0,003, this is equivalent to the 200 ton train running $\frac{0{,}238}{0{,}003} = 79$ km on the level, with a coal consumption of one ton.

This is a consumption of 11,2 kg of coal per km.

(5.) If 93 kw hr of energy are imparted to one ton of ice at 0° C, the ice is transformed into water at 0° C.

∴ If the energy set free by the complete combustion of one ton of coal of a calorific value of 8700 kw hr were entirely transferred to ice at 0° C, then $\frac{8700}{93} = 93{,}5$ ton of ice would be melted. This would have a volume of about 93,5 cu m and corresponds to a cubical block of ice measuring 4,55 meters on each side.

1 kw hr raises one ton of water, by 0,86° C.

∴ The energy of combustion of one ton of coal of a calorific value of 8700 kw hr per ton, is sufficient to raise the temperature of $8700 \times 0{,}86 = 7500$ tons of water by 1° C.

7500 tons of water occupy a cubical space measuring 19,6 meters on each edge.

Thus the energy of combustion of one ton of coal of a calorific value of 8700 kw hr per ton, will: 1. Melt 93,5 tons of ice at 0° C,

or 2. Increase from 0° to 1° C, the temperature of 7500 tons of water.

$\therefore$ The latent heat of ice is $\frac{7500}{93,5} = 80$.

While 93 kw hr is required to melt one ton of ice, $\frac{93}{80} =$ 1,16 kw hr suffices to raise the temperature of one ton of water from 0° to 1° C.

Consider one ton of water at a temperature of 100° C, and at atmospheric pressure. We see from Table III. that 626 kw hr are required to evaporate this ton of water into steam at the same temperature; hence the latent heat of steam at this pressure is

$$\frac{626}{1,16} = 540.$$

In burning one ton of good coal under a boiler, we may transfer to the contents of the boiler 75 per cent. or more of the energy of combustion. To calculate the effect, we may consult Table XI., in which are given values for the energy absorbed in kw hr in raising one ton of water from 50° C to the boiling point at various absolute pressures, and in evaporating it at those pressures and in superheating it 50° C, or 100° C, as may be required.

Table XI. has been derived from Table III.

TABLE XI.

Energy required to raise One Ton of Steam from Water at 50° C to various Pressures and Degrees of Superheat.

Boiler Pressure (abs.) in Kg per Sq Cm, i.e., in Metric Atmospheres.	Kilowatt Hours per Ton of Steam raised from Feed Water at a Temperature of 50° C. Amount of Superheat in Degrees Cent. 0° C. (Sat. Steam).	50° C.	100° C.
8	709	743	776
10	712	748	781
12	715	752	786
14	718	756	791
16	720	759	795
18	721	761	798

It is convenient to consider water at 0° C as devoid of internal energy, and it is merely necessary to make the mental reservation

that this is not strictly the case. In Table XI. we have derived values for the kw hr required to raise one ton of steam from water at 50° C, and this has required deducting from the values in Table III. the kw hr absorbed in increasing the temperature of one ton of water from 0° C to 50° C. Thus from Table III. we find that at an absolute pressure of 10 kg per sq cm, one ton of water at 0° C requires 806 kw hr to convert it into steam with 50° C of superheat. But to raise the temperature of one ton of water from 0° C to 50° C requires $50 \times 1{,}16 = 58$ kw hr, and this amount must be deducted.

$$806 - 58 = 748 \text{ kw hr.}$$

Therefore 748 kw hr are necessary to raise one ton of steam at an absolute pressure of 10 kg per sq cm, and with 50° C of superheat, from water at 50° C. The other values in Table XI. are similarly derived.

From the values in Table XI. we may readily deduce Table XII., in which are set forth the tons of water evaporated per ton of coal of various qualities, and for boiler efficiencies of 60 per cent., 65 per cent., 70 per cent., 75 per cent., and 80 per cent., and for various pressures and superheats.

Since we may obtain from Table XII. the number of tons of steam raised per ton of coal burned, for boiler efficiencies of 60 per cent. to 80 per cent. for given pressures and amounts of superheat, it is a simple step to deduce the fuel cost for producing one ton of steam when burning coal of a given price per ton, and a given calorific value. Fuel costs thus derived are entered up in the second column of Table XIII. for steam raising plants of from 60 per cent. to 80 per cent. efficiency, burning coal of a calorific value of 8700 kw hr per ton and costing, delivered on site, from four shillings to sixteen shillings per ton. The stated boiler efficiencies must be understood to include the overall efficiency of boiler, superheater and steam piping.

Steam driven generating sets consume, according to circumstances, from 6 to 20 kilograms (thousandths of a ton) of steam per kw hr of output from the dynamo. The circumstances affecting the steam consumption per kw hr delivered, excluding the question of type and design, relate mainly to the average percentage of rated load at which the plant operates during the period considered, and to the conditions of admission pressure, superheat and vacuum. We shall not at this stage enter upon the consideration of these points. Assuming that the mean steam consumption per kw hr delivered,

TABLE XII.

Showing, for various Boiler Efficiencies and various Coal Qualities, the Tons of Steam raised per Ton of Coal burned, as a function of the Boiler Pressure and Superheat. Temperature of Feed Water = 50° C.

Calorific Value in Kilowatt Hours per Ton of Coal.		4000 Kilowatt Hours.			5000 Kilowatt Hours.			6000 Kilowatt Hours.			7000 Kilowatt Hours.			8000 Kilowatt Hours.			8500 Kilowatt Hours.			9000 Kilowatt Hours.			9500 Kilowatt Hours.		
Boiler Pressure (absolute) in Kg per Sq Cm.		8	12	16	8	12	16	8	12	16	8	12	16	8	12	16	8	12	16	8	12	16	8	12	16
Boiler Efficiency.	Superheat.	Tons of Steam.			Tons of Steam.			Tons of Steam.			Tons of Steam.			Tons of Steam.			Tons of Steam.			Tons of Steam.			Tons of Steam.		
60 %	0° C.	3,38	3,35	3,33	4,21	4,20	4,16	5,06	5,03	5,00	5,90	5,87	5,83	6,76	6,70	6,66	7,17	7,12	7,07	7,59	7,55	7,50	8,02	7,97	7,91
	50° C.	3,23	3,19	3,16	4,04	3,99	3,95	4,84	4,78	4,74	5,65	5,58	5,53	6,46	6,38	6,32	6,86	6,78	6,71	7,26	7,18	7,11	7,67	7,58	7,50
	100° C.	3,10	3,05	3,02	3,87	3,81	3,77	4,65	4,57	4,54	5,42	5,34	5,28	6,20	6,10	6,04	6,58	6,48	6,41	6,96	6,86	6,79	7,35	7,25	7,17
65 %	0° C.	3,66	3,64	3,61	4,57	4,54	4,51	5,49	5,45	5,41	6,40	6,36	6,32	7,32	7,28	7,22	7,77	7,72	7,67	8,22	8,18	8,12	8,70	8,63	8,57
	50° C.	3,50	3,46	3,43	4,38	4,32	4,28	5,25	5,19	5,13	6,13	6,05	6,00	7,00	6,92	6,85	7,43	7,55	7,28	7,87	7,78	7,71	8,31	8,22	8,14
	100° C.	3,36	3,31	3,27	4,20	4,14	4,09	5,04	4,97	4,90	5,88	5,79	5,72	6,72	6,62	6,54	7,14	7,04	6,95	7,56	7,45	7,36	7,98	7,86	7,76
70 %	0° C.	3,94	3,92	3,89	4,92	4,89	4,86	5,91	5,87	5,83	6,90	6,85	6,80	7,88	7,84	7,78	8,37	8,32	8,26	8,86	8,81	8,75	9,36	9,30	9,23
	50° C.	3,77	3,72	3,68	4,71	4,65	4,60	5,65	5,58	5,52	6,60	6,51	6,44	7,54	7,44	7,36	8,00	7,91	7,81	8,48	8,36	8,29	8,95	8,83	8,74
	100° C.	3,61	3,56	3,52	4,51	4,45	4,40	5,42	5,34	5,28	6,31	6,23	6,16	7,22	7,12	7,04	7,67	7,56	7,48	8.12	8,01	7,92	8,57	8,45	8,36
75 %	0° C.	4,24	4,19	4,16	5,27	5,24	5,20	6,33	6,30	6,25	7,39	7,34	7,29	8,48	8,38	8,32	8,96	8,91	8,85	9,49	9,44	9,37	10,05	9,96	9,89
	50° C.	4,04	3,99	3,95	5,05	4,99	4,94	6,06	5,98	5,93	7,07	6,98	6,91	8,08	7,98	7,90	8,59	8,47	8,40	9,10	8,98	8,89	9,61	9,48	9,33
	100° C.	3,87	3,81	3,77	4,84	4,76	4,71	5,80	5,72	5,66	6,77	6,67	6,60	7,74	7,62	7,54	8,23	8,10	8,01	8,70	8,56	8,48	9,18	9,05	8,95
80 %	0° C.	4,51	4,47	4,44	5,62	5,59	5,55	6,75	6,71	6,66	7,87	7,82	7,77	9,02	8,94	8,88	9,56	9,50	9,44	10,1	10,1	10,0	10,7	10,6	10,5
	50° C.	4,30	4,25	4,21	5,37	5,31	5,26	6,45	6,38	6,31	7,53	7,44	7,36	8,60	8,50	8,42	9,14	9,04	8,95	9,68	9,56	9,48	10,2	10,1	10,0
	100° C.	4,12	4,06	4,02	5,15	5,07	5,03	6,18	6,09	6,04	7,21	7,11	7,04	8,21	8,12	8,04	8,76	8,64	8,55	9,27	9,13	9,05	9,80	9,63	9,55

TABLE XIII.

Cost of Coal in Pence per Kilowatt Hour for various Boiler Efficiencies.

	Cost (delivered on Site) in Shillings per Ton of Coal of a Calorific Value of 8700 Kilowatt Hours per Ton.	Outlay for Fuel (in Shillings per Ton of Steam raised) in producing (from Feed Water at 50° C) Steam at an absolute pressure of 13 Kg per Sq Cm and 50° C Superheat.	Cost of Coal in pence per Kilowatt Hour (absolute pressure of Steam 13 Kg per Sq Cm 50° C Superheat. Feed Water 50° C) at a Steam Consumption of							
			6	8	10	12	14	16	18	20
			Kilograms per Kilowatt Hour.							
For a Boiler Efficiency 60%	4s.	0,57	0,041	0,055	0,069	0,083	0,097	0,110	0,124	0,100
	5s.	0,71	0,052	0,069	0,086	0,103	0,121	0,138	0,155	0,175
	6s.	0,86	0,062	0,083	0,104	0,124	0,145	0,166	0,186	0,207
	7s.	1,01	0,072	0,097	0,121	0,145	0,169	0,193	0,217	0,242
	8s.	1,15	0,083	0,110	0,138	0,166	0,193	0,221	0,248	0,276
	9s.	1,30	0,093	0,124	0,155	0,187	0,217	0,248	0,280	0,310
	10s.	1,44	0,104	0,138	0,173	0,207	0,241	0,276	0,310	0,345
	11s.	1,58	0,114	0,152	0,190	0,228	0,266	0,304	0,342	0,379
	12s.	1,72	0,124	0,166	0,207	0,249	0,290	0,331	0,373	0,414
	13s.	1,87	0,134	0,180	0,224	0,269	0,314	0,359	0,404	0,448
	14s.	2,02	0,145	0,193	0,242	0,290	0,338	0,386	0,435	0,483
	15s.	2,16	0,155	0,207	0,259	0,311	0,362	0,414	0,466	0,517
	16s.	2,30	0,165	0,221	0,276	0,331	0,386	0,441	0,497	0,552
For a Boiler Efficiency 65%	4s.	0,53	0,039	0,051	0,064	0,077	0,090	0,103	0,115	0,128
	5s.	0,66	0,048	0,064	0,080	0,096	0,112	0,128	0,144	0,162
	6s.	0,81	0,058	0,077	0,096	0,116	0,135	0,154	0,173	0,193
	7s.	0,94	0,067	0,090	0,112	0,135	0,157	0,180	0,202	0,225
	8s.	1,07	0,077	0,103	0,128	0,154	0,180	0,206	0,231	0,257
	9s.	1,21	0,087	0,115	0,144	0,174	0,202	0,230	0,260	0,289
	10s.	1,34	0,097	0,128	0,160	0,193	0,224	0,256	0,288	0,320
	11s.	1,47	0,106	0,141	0,176	0,212	0,247	0,283	0,317	0,352
	12s.	1,61	0,116	0,154	0,192	0,231	0,268	0,308	0,346	0,385
	13s.	1,74	0,125	0,167	0,208	0,250	0,292	0,335	0,375	0,416
	14s.	1,87	0,135	0,180	0,224	0,270	0,314	0,360	0,404	0,449
	15s.	2,00	0,144	0,192	0,240	0,289	0,336	0,386	0,433	0,481
	16s.	2,13	0,154	0,205	0,256	0,308	0,358	0,412	0,462	0,513
For a Boiler Efficiency 70%	4s.	0,49	0,036	0,047	0,059	0,071	0,083	0.095	0,106	0,118
	5s.	0,61	0,044	0,059	0,074	0,089	0,103	0,118	0,133	0,148
	6s.	0,74	0,053	0,071	0,089	0,107	0,124	0,142	0,160	0,178
	7s.	0,86	0,062	0,083	0,103	0,124	0,145	0,166	0,186	0,207
	8s.	0,98	0,071	0,095	0,118	0,142	0,166	0,190	0,213	0,237
	9s.	1,11	0,080	0,106	0,133	0,160	0,187	0,213	0,240	0,266
	10s.	1,23	0,089	0,118	0,148	0,178	0,207	0,237	0,267	0,295
	11s.	1,35	0,098	0,130	0,162	0,195	0,228	0,261	0,294	0,325
	12s.	1,47	0,107	0,143	0,177	0,213	0,249	0,285	0,320	0,355
	13s.	1,60	0,115	0,154	0,192	0,231	0,269	0,310	0,346	0,385
	14s.	1,72	0,124	0,166	0,207	0,249	0,290	0,334	0,373	0,415
	15s.	1,84	0,133	0,177	0,222	0,266	0,310	0,357	0,400	0,444
	16s.	1,96	0,142	0,189	0,236	0,284	0,331	0,380	0,426	0,474
For a Boiler Efficiency 75%	4s.	0,46	0,033	0,044	0,055	0,066	0,078	0,089	0,100	0,111
	5s.	0,58	0,041	0'055	0,069	0,083	0,097	0,110	0,125	0,139
	6s.	0,69	0,050	0,067	0,083	0,100	0,116	0,133	0,150	0,167
	7s.	0,81	0,058	0,078	0,097	0,116	0,136	0,155	0,175	0,194
	8s.	0,92	0,066	0,089	0,111	0,133	0,156	0,178	0,200	0,222
	9s.	1,04	0,075	0,100	0,125	0,150	0,175	0,200	0,225	0,250
	10s.	1,15	0,083	0,111	0,138	0,166	0,194	0,222	0,250	0,276
	11s.	1,26	0,091	0,122	0,152	0,183	0,213	0,244	0,275	0,304
	12s.	1,38	0,100	0,133	0,167	0,200	0,234	0,267	0,300	0,333
	13s.	1,50	0,108	0,144	0,180	0,216	0,242	0,290	0,325	0,362
	14s.	1,61	0,116	0,155	0,194	0,234	0,272	0,311	0,350	0,389
	15s.	1,72	0,124	0,166	0,208	0,250	0,292	0,333	0,375	0,416
	16s.	1,84	0,133	0,177	0,222	0,266	0,353	0,355	0,400	0,444
For a Boiler Efficiency 80%	4s.	0,43	0,031	0,041	0,052	0,062	0,072	0,083	0,093	0,103
	5s.	0,54	0,039	0,052	0,065	0,078	0,091	0,104	0,116	0,130
	6s.	0,64	0,046	0,061	0,078	0,093	0,100	0,124	0,139	0,155
	7s.	0,75	0,054	0,072	0,091	0,109	0,127	0,145	0,162	0,182
	8s.	0,86	0,062	0,083	0,104	0,124	0,145	0,166	0,186	0,206
	9s.	0,96	0,070	0,093	0,117	0,140	0,163	0,186	0,210	0,233
	10s.	1,08	0,078	0,103	0,130	0,155	0,181	0,206	0,234	0,260
	11s.	1,18	0,085	0,114	0,143	0,171	0,200	0,227	0,257	0,285
	12s.	1,29	0,093	0,124	0,156	0,186	0,218	0,248	0,280	0,310
	13s.	1,40	0,101	0,135	0,169	0,203	0,236	0,269	0,304	0,337
	14s.	1,50	0,109	0,145	0,182	0,218	0,254	0,290	0,327	0,364
	15s.	1,61	0,116	0,176	0,195	0,233	0,272	0,311	0,360	0,390
	16s.	1,72	0,124	0,166	0,207	0,248	0,290	0,331	0,372	0,414

NOTE.—These "Boiler Efficiencies" must be taken as including Boilers, Superheaters and Steam Piping.

and quality of coal, and for the from the right-hand section of nce per kw hr delivered from other calorific value, the fuel cost calorific values. Let us apply

= 70 per cent.
llings per ton.
ption = 9 kg per kw hr.
al = 7000 kw hr per ton.

relating to 70 per cent. boiler n, we find for steam consumpespectively, coal costs of 0,118

of 9 kg per kw hr we obtain a
0 18

× ,133
pence per kw hr.

Generating Stations.—A very interesting with which electrical engineering calculat, may be found in the calculation of the g station, this efficiency being defined as the hours delivered from the generating station e kilowatt-hours of calorific value of the coal year.

this calculation for a representative generating Britain. During twelve months 1,5 million kw hr rom this station, and this was employed for lighting The load factor[1] was 22 per cent., and the station densing. The coal burned had a calorific value of per ton. 6700 tons were burned during the year. total energy of combustion for the year, amounted to

$$7500 \times 6700 = 50 \text{ million kw hr.}$$

he overall efficiency of the generating station was

$$\frac{1,5}{50} = 3,0 \text{ per cent.}$$

ile this is not a good result, it is nevertheless typical of the at majority of generating stations of this type and capacity. A

[1] The load factor is the ratio of the average output taken over the 8750 hours a year, to the maximum output at any time during the year.

condensing station of this output should, however, show at least 5 per cent. efficiency. With large modern stations, efficiencies of over 7 per cent. are often attained. Thus for the year ending June 30th, 1904, the efficiency of the Berlin Electricity Works, with an output of 113 million kw hr from a number of distributed generating stations, works out at 9,6 per cent., and the efficiency obtained by this company for the year ending June 30th, 1905, when the output had risen to 141 million kw hr, was 10 per cent. For the year ending June 30th, 1906, the output of the Berlin Electricity Works was 167 million kw hr, and the overall efficiency was 10,3 per cent.

The overall efficiency of the generating station of the Glasgow Corporation Tramways, for the year ending May 31st, 1906, and with an output of 26 million kw hr, was 9,6 per cent. The Sheffield Corporation Tramways, for the same year, had an output of 14,5 million kw hr from the generating station, and an efficiency of 7,8 per cent.

From the various sources from which this data was brought together, it appeared that the average price paid for coal, and the calorific value of the coal used in these plants, was as shown in Table XIV.

TABLE XIV.

Cost and Calorific Value of Coal used in various Generating Stations.

	Cost of Coal in Shillings per Ton.	Calorific Value in Kilowatt Hours per Ton.
Berlin Electricity Works (1905) ...	16,0	8 100
Glasgow Corporation Tramways (1906)	6,4	8 100
Sheffield Corporation Tramways (1906)	8,2	7 700.

From the data in Table XIV. we may deduce, as in Table XV., the fuel cost per kw hr of calorific value of the coal, and then, dividing by the efficiency, also the fuel cost per kw hr of output from the generating stations.

Given the cost of coal in shillings per ton, its calorific value in kw hr per ton, and the efficiency of the generating station in per cent., then the fuel cost in pence per kw hr of annual output from generating station

$$= \frac{1200 \times \text{Cost of coal}}{\text{Calorific value} \times \text{Efficiency}}$$

TABLE XV.

Fuel Cost per Kilowatt Hour Output from Generating Stations given in Table XIV.

	Cost per Kilowatt Hour of Calorific Value of Fuel in Pence.	Efficiency of Generating Station or Stations.	Fuel Cost per Kilowatt Hour Output from Generating Stations in Pence.
Berlin Electricity Works (1905) ...	0,0245	10,0	0,245
Glasgow Corporation Tramways (1906)	0,0095	9,6	0,099
Sheffield Corporation Tramways (1906)	0,0127	7,8	0,164

Thus in the case of the Sheffield Corporation Tramways, we have —fuel cost per kw hr of annual output from the generating station,

$$= \frac{1200 \times 8,2}{7700 \times 7,8} = 0,164 \text{ pence}$$

Let us suppose that the Sheffield Corporation Tramways had substituted a coal of a calorific value of 9000 kw hr per ton, for which a price of 11 shillings per ton was paid, and that the efficiency of the steam-raising plant was unaffected by this change in the quality of the coal burned. The fuel cost per kw hr of annual output from the generating station would have become

$$\frac{1200 \times 11}{9000 \times 7,8} = 0,188 \text{ pence.}$$

Instead, however, of burning 24 000 tons of coal per year, only $\frac{7700}{9000} \times 24\,000 = 20\,500$ tons of the better coal should be required, and hence savings in other directions could be made as the result of the lesser weight of coal to be handled. Moreover, the efficiency of the steam plant would generally be affected by a change in the grade of fuel.

Suppose the efficiency to have been increased to 8,2 per cent. (from 7,8 per cent.), then the fuel cost with the new fuel would have become

$$\frac{1200 \times 11}{9000 \times 8,2} = 0,179 \text{ pence per kw hr of annual output.}$$

It is a matter requiring considerable investigation to determine,

in any particular case, the most economical grade of coal to be burned. It involves also a consideration of the type and proportions of boiler, of grate, of stoking arrangements, as well as of the cost of modifying or replacing certain of these arrangements with others more suitable to other grades of fuel.

It has already been pointed out that Works commonly designated

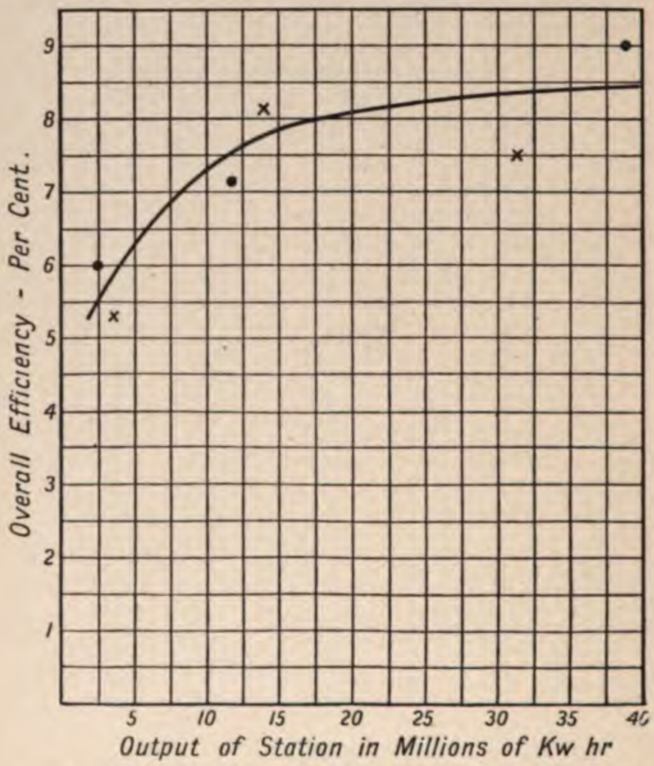


Fig. 8.—Curve Showing the Average Overall Efficiencies of Generating Stations of Various Capacities (see p. 31).
x = Stations in Great Britain.
● = Stations Abroad.

"Generating Stations" should, strictly speaking, be termed "Transforming Stations," since in such stations we transform a small part of the energy of combustion of the coal or other fuel, into electrical energy. At the same time we—unwillingly—transform a far larger part of the energy of combustion of the coal into irrecoverable heat energy.

TABLE XVI.

Annual Outputs and Annual Overall Efficiencies of 26 Generating Stations. These Stations are all Steam Driven and burn Coal.

Class.	Reference Number.	Name of Station.	Millions of Kilowatt Hours Delivered from Generating Station per Year.	Quality of Coal.	Tons of Coal per Annum.	Average Price of Coal in Shillings Per Ton.	Calorific Value in Kilowatt Hours per Ton.	Total Input in Millions of Kilowatt Hours of Calorific Value.	Total Output in Millions of Kilowatt Hours of Electrical Energy.	Annual Overall Efficiency in per Cent.
Between 1,0 and 5,1 Millions of Kilowatt Hours per Year.	I.	Würzburg	1,10	Large Rühr Nuts . . .	2150	22,3	8600	18,5	1,10	6,0 %
	II.	Barrow	1,16	Carlton Rough Slack . .	3100	11,0	9000	28,0	1,16	4,1 %
	III.	Rheydt	1,19	Rühr and Wurm Nuts . .	3180	11,9	8400	26,7	1,19	4,5 %
	IV.	Harrogate	1,4	Hard Steam Nuts . . .	3900	11,3	7700	30,0	1,40	4,6 %
	V.	Darmstadt	1,5	Westphalian Anthracite Nuts	3790	20,1	8100	30,7	1,50	4,9 %
	VI.	Crefeld	2,87	Nuts	4870	14,0	9000	43,8	2,87	6,5 %
	VII.	Derby	3,3	Small Peas	11000	7,3	9100	100	3,30	3,3 %
	VIII.	Burnley	3,4	Pea Nuts	5800	10,4	9000	52,0	3,40	6,6 %
	IX.	Königsberg . . .	3,63	Various	7400	15,7	7200	53,2	2,63	6,8 %
	X.	Dundee	4,3	Polmaise	8300	7,7	7100	59,0	4,30	7,3 %
	XI.	Aachen	4,42	—	7360	13,2	8350	61,5	4,42	7,2 %
	XII.	Hull	5,1	South Yorkshire Steam and Unwashed Slack . . .	16000	9,5	9500	150	5,10	3,4 %
Between 7 and 16 Millions of Kilowatt Hours per Year.	XIII.	Budapest	7,4	Hungarian Small and Slack .	22440	13,0	5700	128	7,4	5,8 %
	XIV.	Leipzig	9,4	Meuselwitzer Small Coal .	46010	5,0	2800	129	9,4	7,3 %
	XV.	Dublin United Tramways	10,8	Nut Coal.	16000	9,7	8020	130	10,8	8,3 %
	XVI.	Salford Corporation .	13,7	Slack	20000	8,7	9320	190	13,7	7,2 %
	XVII.	Sheffield Tramways . .	14,5	Washed Nuts and Dry Nuts .	24000	8,0	7700	185	14,5	7,8 %
	XVIII.	Genoa	15,1	Cardiff Coal	21880	—	8700	190	15,1	8,0 %
	XIX.	Cöln	15,1	Coke Briquettes and Nuts .	23420	12,8	8800	206	15,1	7,3 %
	XX.	Leeds Corporation . .	16,0	Slack	22000	7,7	7000	170	16,0	9,4 %
Between 18 and 56 Millions of Kilowatt Hours per Year.	XXI.	Central London Railway	18,1	—	30200	16,5	9300	290	18,1	6,3 %
	XXII.	Glasgow Tramways . .	26,0	Slack	31000	6,4	8100	250	26,0	10,4 %
	XXIII.	Buenos Aires . . .	29,6	Cardiff	43800	—	8750	383	29,6	7,7 %
	XXIV.	Hamburg	30,8	Westphalian Slack . . .	43480	16,5	8700	380	30,8	8,1 %
	XXV.	Manchester Corporation .	51,0	Washed Lancashire Slack .	86000	9,1	8940	770	51,0	6,6 %
	XXVI.	Vienna	55,2	Various	65560	—	7550	495	55,2	11,1 %

The author has analysed the results of a number of generating stations with the object of determining the efficiency from the coal bunkers to the outgoing mains. We shall denote this efficiency as the "Annual Overall Efficiency" of the generating station.

Twenty-six of these generating stations are classified in three groups in Table XVI. In each group, one-half represents British

TABLE XVII.

Further Details of the twenty-six Generating Stations.

Reference Number.	Results for Year Ending	Year o Working.	Use of Energy; L = Lighting P = Power T = Traction.	Annual Load Factor.	Steam Pressure in Kg per Sq Cm.	Superheat in Deg Cent.	Exhaust Pressure in Kg per Sq Cm.
I.	1905	7th	L.P.T.	41	10	—	—
II.	1906	7th	L.T.	12,8	10,5	70° C.	0,17 to 0,2
III.	1905	5th	L.P.T.	17	10	—	—
IV.	1906	9th	L.	14,5	9,5	80° C.	0,03
V.	1905	17th	L.P.T.	46,5	8,0	—	—
VI.	1905	6th	L.P.T.	—	10	—	—
VII.	1906	12th	L.P.T.	16,2	—	30° C.	—
VIII.	1906	12th	L.P.T.	20,9	11	50° C.	0,13
IX.	1905	15th	L.P.T.	—	12	—	—
X.	1906	13th	L.T.	16,6	11	70° C.	0,50
XI.	1905	13th	L.P.T.	—	12	—	—
XII.	1906	13th	L.	11,9	11	—	—
XIII.	1905	13th	L.P.	35	12	—	—
XIV.	1905	10th	T.	16,5	12	—	—
XV.	1906	9th	T.	—	11	—	—
XVI.	1906	10th	L.P.T.	28,5	11	50° C.	0,13
XVII.	1906	6th	T.	—	11	55	0,13
XVIII.	1905	11th	L.P.T.	—	12	—	—
XIX.	1905	14th	L.P.T.	37,5	12	—	—
XX.	1906	8th	T.	—	9—13	20—55	0,13
XXI.	1905	5th	T.	—	11	0	0,12
XXII.	1906	7th	T.	31,0	—	—	—
XXIII.	1904	5th	L.P.T.	—	14	—	—
XXIV.	1905	17th	L.P.T.	—	12	—	—
XXV.	1906	12th	L.P.T.	21,2	14	60° C.	0,07
XXVI.	1905	4th	L.P.T.	39,4	14	—	—

stations, and one-half represents stations outside of Great Britain. None of the stations are situated in the United States, as the data studied did not comprise any such stations. Two considerations controlled the choice of stations for inclusion in the investigation. The first consideration was that the available data should comprise as many as possible of the conditions affecting the annual overall

efficiency. The second consideration was that the range of capacities and the average capacity of the British stations should be about equal to the range of capacities and the average capacity of the stations located outside of Great Britain. The selection was made without any reference whatever to the value of the resulting average efficiencies.

The stations are arranged in the order of their annual outputs, beginning with a small station with an annual output of about one million kw hr, and concluding with a station with an annual output of 55 million kw hr. In Table XVI. is also compiled the necessary data for determining the annual overall efficiency of each station.

In Table XVII. are recorded various particulars of the stations which could be expected to have a bearing upon the efficiency.

In Table XVIII. these results are averaged for the British stations, and for the stations situated outside of Great Britain. From this Table is plotted the curve shown in Fig. 8, which may be fairly said to represent modern practice for generating stations working under average conditions.

TABLE XVIII.

Average Overall Efficiencies of Stations given in Table XVI.

Class.	Great Britain (B) or Abroad (A).	Average Output from Generating Station during Year in Millions of Kw Hr.	Average Efficiency of Generating Station.
Between 1,0 and 5,1 millions of kw hr per year.	B A	3,6 2,5	4,9 6,0
Between 7 and 16 millions of kw hr per year.	B A	13,6 11,7	8,2 7,1
Between 18 and 56 millions of kw hr per year.	B A	31,7 38,5	7,7 9,0

It is a pity that the published returns from generating stations are not more complete. Thus we naturally ask ourselves whether

it might not be possible to trace a connection between the overall efficiency and the extent to which electrical storage batteries are employed, but we find that the incompleteness of our data makes this impossible. It is fair to assume that all these stations were operated condensing, although this fact is recorded only in the case of the British stations. In fact, non-condensing stations, when known to be such, were purposely excluded from the comparison. In but few cases, however, have we records of the average exhaust pressure maintained, or of the average amount of superheat employed. The comparison of the capital cost and of the rate of depreciation would also have been impracticable, and hence one cannot say that the one or the other set of generating stations represents the better engineering.

Analysis of Losses in Supply System.—Another important omission from the published returns of British generating stations, is the annual output *from the station*. The amount recorded is generally the amount of energy actually used by the consumers. The difference between the two amounts represents the energy lost in transmission. In Table XVI. the output entered for the British stations has been obtained by increasing the amount of energy *sold* during the year, by 25 per cent., or in other words, the transmission loss has been assumed to be 20 per cent. of the energy generated. That this value is a sufficiently fair approximation for the purpose, is indicated by the results of an analysis of twelve continental generating stations for the year 1904. For these cases the average transmission losses were as follows:—

Loss in feeders . .	12 per cent.	All expressed as percentage of energy generated.
,, ,, accumulators .	7 ,, ,,	
,, ,, distributors .	6 ,, ,,	
Total	25 per cent.	

Still higher values were obtained for five continental towns that included transformers in their transmission system:—

Loss in Feeders	3 per cent.
,, ,, Accumulators	3 ,, ,,
,, ,, Transformers	17 ,, ,,
,, ,, Distributors	8 ,, ,,
	31 per cent.

Setting aside minor considerations, it is quite evident that the efficiency curve of Fig. 8 is very low. The efficiency of steam generating sets at full load, frequently exceeds 20 per cent. in larger sizes when operated under reasonably economic conditions of pressure, superheat and vacuum, and the efficiency of the steam raising plant when working at its rated capacity should not fall below 74 per cent. Taking the efficiency of the steam piping at

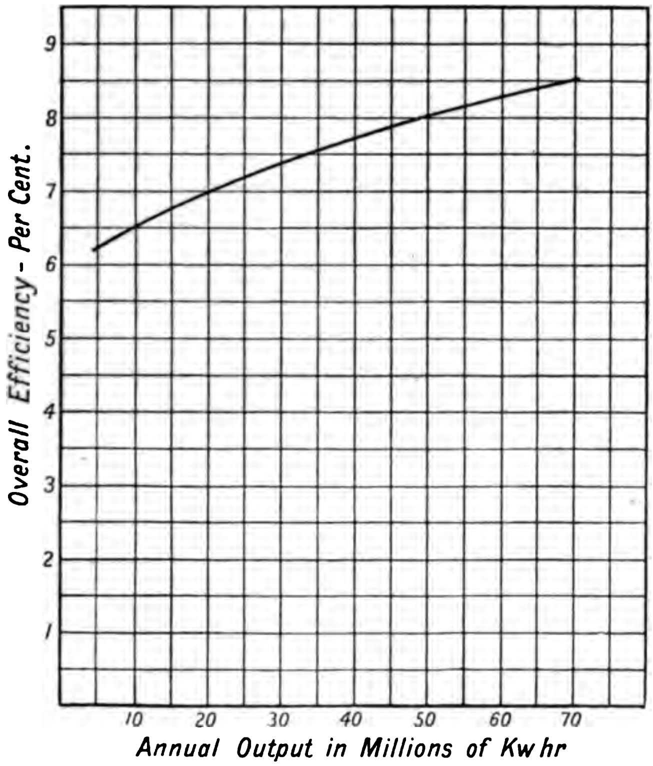


Fig. 9. EFFICIENCIES OF STATIONS AS GIVEN BY PATCHELL.

95 per cent., we obtain a practicable full load overall efficiency of the generating station of

$$0,20 \times 0,74 \times 0,95 = 14,0 \text{ per cent.}$$

The difference between this efficiency and that actually obtained in practice, is due chiefly to the circumstances that the plant is run for a large part of the time at considerably less than full load; that fires must be kept up under one or more spare boilers; that the boilers and engines are not maintained in the condition

of highest efficiency; that the supply of air to the fires is not suitably regulated; that the coal is not uniformly of the calorific

TABLE XIX.

Particulars of Stations given by Patchell.

Group.	Station.	Output in Millions of Kw Hr.	Kg of Coal per Kw Hr.	Calorific Value in Kw Hr per Ton.	Kw Hr Input per Kw Hr Output.	Efficiency.	Load Factor (per Cent.)
I.	Sheffield (Neepsend)	3,5	1,83	8400	15,4	6,50	13,4
	Powell Duffryn Steam Coal Co.	4,5	1,70	8400	14,3	7,00	37,0
	City and South London Railway	6,6	2,00	7400	14,8	6,75	35,0
	St. James and Pall Mall Co.	6,7	2,51	9200	23,1	4,33	18,6
	Charlottenburg, 1904	6,7	2,04	7340	15,0	6,66	24,6
	Central Electric Co.	7,1	1,00	9000	17,1	5,85	12,5
	Elberfeld, 1904	7,2	1,36	8000	10,9	9,17	27,2
	Leeds	8,4	3,24	7100	23,0	4,35	14,5
II.	Charing Cross Co. (Bow, 1904)	10,3	1,56	9700	15,1	6,62	13,1
	Salford	13,7	1,98	9250	18,3	5,46	28,0
	County of London Co.	11,4	2,50	7100	17,8	5,61	18,9
	Westminster	11,6	2,25	9300	21,0	4,76	27,0
	Charing Cross Co. (Bow, 1905)	12,2	1,65	9000	14,8	6,72	13,7
	Hamburg (Zollverein), 1904	12,9	1,36	8700	11,8	8,47	38,6
	Munich, 1904	12,9	1,68	8200	13,8	7,25	24,2
	Cologne, 1904	13,1	1,63	8300	13,5	7,40	37,8
III.	Copenhagen, 1904	13,3	1,77	8100	14,3	7,00	29,3
	London Electric Supply Co.	14,2	2,08	7750	16,1	6,20	25,0
	Newcastle (Carville for 6 Months)	14,6	1,42	7100	10,1	9,95	37,0
	Bradford	14,7	1,87	8400	15,7	6,37	28,0
	Dresden, 1904, Power and Light	18,0	3,07	5200	15,8	6,33	29,0
	Frankfort, 1904	18,5	1,53	8700	13,3	7,50	29,8
	Glasgow Corporation	20,6	2,04	6800	13,9	7,20	17,4
	Metropolitan E. S. Co.	22,7	2,10	7600	16,0	6,25	22,0
IV.	Hamburg (Combined), 1904	27,2	1,54	8700	13,4	7,46	28,4
	Oberschlesischer Industrie-Bezirk	27,3	2,18	7000	15,3	6,54	35,2
	Manchester (Stuart St.)	28,2	1,62	8700	14,1	7,10	36,3
	Vienna, 1904	45,9	1,22	7700	9,4	10,6	35,2
	Boston (Mass., U.S.A.), Edison	49,9	1,21	9500	11,5	8,70	28,2
	Berlin, 1904	113,4	1,40	8100	11,4	8,77	31,1
	Chicago (Fisk St.) Edison	130,2	2,04	6500	13,3	7,52	33,0
	Berlin, 1905	141,1	1,08	8000	8,64	11,6	30,4

value of the samples tested, and to various other detail circumstances. While improvement should be made in all these respects, it is not reasonable to expect that 14 per cent. efficiency should at present be

obtained. In plants of large capacity, however, it should be more closely approached than is at present the case.

As is shown in Table XVI., it is not unusual to find large stations with an annual overall efficiency of over 9 per cent.

In a contribution to the Proceedings of the Institution of Electrical Engineers,[1] Patchell has published some tables of data giving the coal consumption, the calorific value, the load factor, and the annual output for quite a number of generating stations. The author has rearranged Patchell's figures according to the units used in the present work, and they are given herewith in Table XIX.

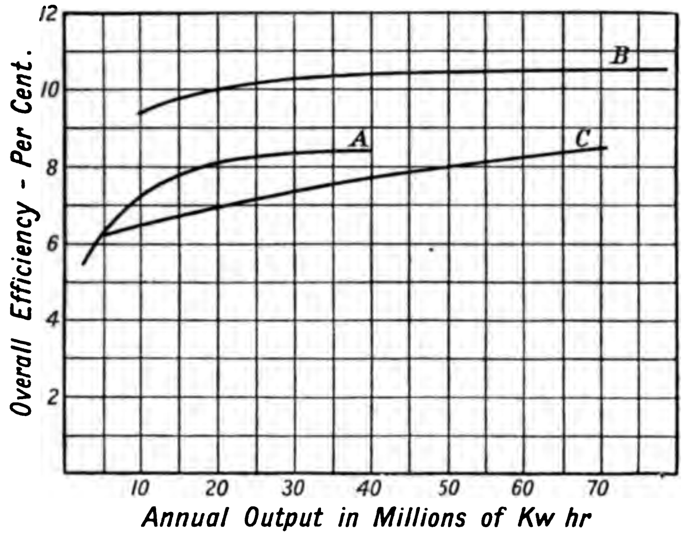


Fig. 10. Efficiencies of Stations.

Curve A from Fig. 8, on p 28.—Author's investigation.
Curve B from Fig. 18, on p. 54.—Attainable values.
Curve C. from Fig. 9, on p. 33.—Patchell's investigation.

arranged in the order of increasing annual outputs in millions of kilowatt hours. The author has divided these thirty-two results into four groups of eight stations each, and arranged in the order of increasing capacities of the stations.

The averages for these four groups are given in Table XX., and they are plotted in the curve of Fig. 9. In Fig. 10 are repeated the curves of Figs. 8 and 9, and there is also added the curve of Fig. 18 on p. 54, which represents values which, it would appear,

[1] *Journal I. E. E.*, vol. xxxvi., p 156.

ought to be attained. The derivation of Fig. 18 is discussed on p. 53.

TABLE XX.

Average Results for Stations given by Patchell.

Group.	Average Output in Millions of Kw Hr per Annum.	Average Load Factor.	Average Efficiency.
I.	6	23	6,3
II.	12	25	6,5
III.	17	27	7,1
IV.	70	32	8,5

It is evident from an examination of Fig. 10, that there is a fair agreement between the results of the author's own analysis of existing generating stations of various capacities and Patchell's results. The former curve shows somewhat higher values than the latter, partly owing to the fact that many of the results are more recent. In Table XXI. are set forth fair representative figures for the values at present obtained, and the values which ought to be readily obtained. These are roughly estimated for 30 per cent. and for 50 per cent. load factors.

TABLE XXI.

Average Overall Efficiencies of Generating Stations. For 30 per Cent. and 50 per Cent. Load Factor.

Capacity of Station in Millions of Kw Hrs per Annum.	Load Factor = 30 Per Cent.		Load Factor = 50 Per Cent.	
	Overall Efficiency now obtained.	Overall Efficiency which should be Obtainable.	Overall Efficiency now obtained.	Overall Efficiency which should be Obtainable.
6	6,8	7,2	7,3	8,2
12	7,0	8,1	7,8	9,2
17	7,2	8,6	8,2	9,6
70	8,4	9,8	9,1	10,5

Analysis of Losses in Generating Station.—It is very instructive to note that of the total heat available from the combustion of coal or other fuel, only 11 per cent., under most favourable conditions, is transformed into useful work. It is interesting to examine where the remaining 89 per cent. is lost. The various losses which occur during the process of transformation from heat to electrical or

mechanical energy are allocated by various authorities in the proportions shown in Table XXII., where the figures given by Professor Dalby, H. C. Stott (in a paper read before the American Institute of Electrical Engineers),[1] and by "Power" in a pamphlet published in 1904, are placed in parallel columns. It is seen that there is a very fair agreement between the figures. It is as well to remember when comparing the results that no economiser is used by Professor Dalby, or by "Power," although in the latter case a large amount of heat is returned by the feed-water heater. Professor Dalby's figures are less recent than the others, which are actual test results, made under working conditions.

In Figs. 11, 12 and 13, the figures given in Table XXII. are diagrammatically represented by a stream of energy, the various losses being represented by small branch streams. The energy ultimately available at the bus bars is represented by a thick black stream. This graphical method of showing the losses is due to Professor Dalby.

It is interesting to note the large percentage of heat rejected to the condenser, due to the low thermal efficiency of all steam engines.

TABLE XXII.

Showing Losses during Transformation of Energy contained in Coal into Mechanical or Electrical Energy.

Source of Loss.	Percentage of Loss of Total Heat as given by the following:		
	Prof. Dalby.	H. C. Stott.	"Power."
Radiation and ashes . .	7	10,4	6,0
Chimney	27	22,7	22,0
Rejected to condenser . .	53	60,1	57,3
Minor losses . . .	10,4	6,4	10,3
Total losses	97,4	99,6	95,6
Heat returned by feed water	5,0	3,1	5,0
Heat returned by economiser		6,8	
Net losses	92,4	89,7	90,6
Total energy in coal . .	100,0	100,0	100,0
Efficiency	7,6	10,3	9,4

[1] "Power Plant Economics," *Trans. Am. Inst. Elec. Engrs.*, vol. xxv. (1906), p. 1.

Demand for Electricity.

It is a difficult matter to predetermine the demand for electricity. Local conditions vary so widely that it is impossible to obtain a very accurate estimate either of the demand or of the

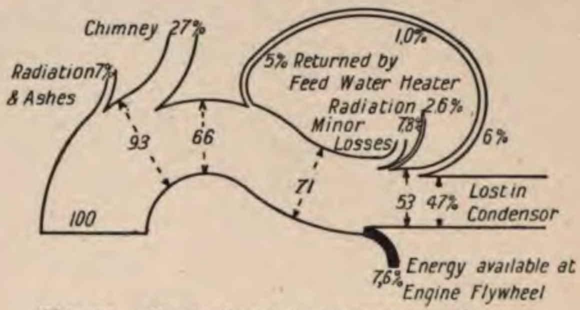


Fig. 11. Prof. Dalby's Analysis of Losses.

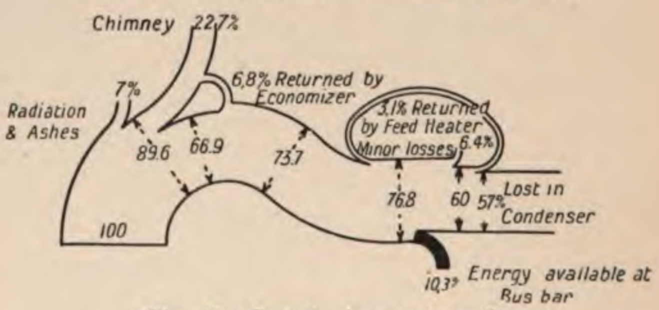


Fig. 12. Stott's Analysis of Losses.

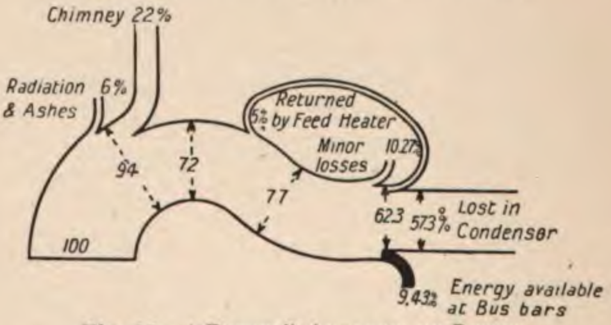


Fig. 13. "Power" Analysis of Losses.

Figs. 11, 12 and 13. Analysis of Losses in Steam Generating Plant.

growth of the demand from year to year. Nevertheless, it is possible by analysis of a number of undertakings to make a rough estimate of the prospects of a power supply serving a large densely populated

area such as a large manufacturing city. We have made such an analysis in the following pages, and, as an illustrative example, we have at the same time worked out rough estimates for a city of one million inhabitants.

Interior Lighting.—Analysis of returns for twenty-two large towns in Great Britain, with populations ranging from 800 thousand down to 50 thousand, show that for every thousand inhabitants there are some 800 eight c p lamps (or the equivalent in larger candle power), connected, *i.e.*, 0,8 lamp per person.

The average number of kw hr per lamp per year works out at 17 at the customers' meters. The data on which these averages is based is set forth in Table XXIII.

TABLE XXIII.

Table of Interior Lighting of various British Towns.

No.	Place.	Population. Thousands.	No. of 8 c p Glow Lamps per Inhabitant.	Kw hr per Lamp Year.
1	Newcastle-on-Tyne .	400,0	2,1	Not obtainable
2	Sheffield . . .	413,0	0,82	14,6
3	Leeds . . .	450,1	0,8	21,1
4	Birmingham . .	522,2	0,5	19,2
5	Manchester . .	698,3	1,05	22,0
6	Liverpool . . .	702,2	0,83	18,7
7	Glasgow . . .	800,0	1,0	20,9
8	Cardiff . . .	172,6	0,63	24,9
9	Newcastle District .	214,9	0,47	28,1
10	Leicester . . .	220,0	0,85	11,0
11	Hull	250,0	0,96	14,0
12	West Ham . .	275,4	0,81	29,1
13	Huddersfield . .	95,0	1,4	12,6
14	Bournemouth . .	106,0	1,1	11,8
15	East Ham . .	104,0	0,82	16,0
16	Preston . . .	120,0	0,83	18,7
17	Oldham . . .	137,2	0,42	15,4
18	Darlington . .	49,0	0,67	13,1
19	Tynemouth . .	51,6	0,62	17,1
20	Stockton . . .	51,5	0,48	15,6
21	Ilford . . .	55,0	0,96	28,3
22	Wallasey . . .	56,5	0,59	13,7
		Average .	0,805	17,1

The c p values are expressed in terms of the equivalent number of 8 c p incandescent lamps, when arc lamps or other types of incandescent lamps are employed.

On the basis of 3,5 watts per c p an 8 c p lamp requires

$$3{,}5 \times 8 = 28 \text{ watts}$$

i.e., 28 watt hours per hour.

The average hours burning per year is therefore

$$\frac{17 \times 1000}{28} = 610$$

or $\frac{610}{365} = 1{,}66$ hours per day.

The above figures are from stations which on the average have been running for about ten years. Of course the precise number of lamps per inhabitant varies widely according to local conditions, such as the amount of competition by gas lighting, the amount of lighting required during the daytime in consequence of fogs, and still more upon the enterprise of the conductors of the undertaking. Included in this last condition is the price per kw hr. For one million inhabitants we should expect, on the basis of eight-tenths of an eight candle-power lamp per inhabitant, a total of 800 000 eight candle-power lamps.

A year or two ago we should have based our estimates on some such lamp efficiency as 3,5 watts per candle. With the rapid progress now being made in improving the incandescent lamp, as shown, for instance, by Tantalum, Osmium, Tungsten and Nernst lamps, we could greatly reduce this value. Although, however, these lamps have efficiencies better than two watts per candle, their introduction will necessarily be slow, and a large percentage of the lamps will for some years continue to be of the carbon filament type and of some such economy as 3,5 watts per candle. Hence for an average value, we should not, for the next two or three years, be safe in assuming less than 2,5 watts per candle.

If the lamps burn on the average 1,7 hours per day, at 2,5 watts per candle, the consumption per lamp per day will be

$$2{,}5 \times 8 \times 1{,}7 = 34 \text{ watt hours.}$$

The consumption per lamp-year is thus

$$\frac{34 \times 365}{1000} = 12{,}4 \text{ kw hr.}$$

For 800 000 lamps the total number of kw hr required will be

$$12{,}4 \times 0{,}80 = \text{ten million kw hr per year.}$$

Allowing 15 per cent. loss in transmission and distribution we must generate $\frac{10}{0{,}85} = 11{,}7$ million kw hr per year to provide for interior lighting.

Street Lighting.—For four large continental cities for which the returns were examined, the ratio of the consumption for public arcs to that for private lighting is as set forth in Table XXIV.

TABLE XXIV.

Table of Public Lighting Supply for four Continental Towns, showing relation to Private Lighting.

No.	Town.	Kw hr used for Public Arcs.	Kw hr used for Private Arcs.	Kw hr used for Private Glow Lamps.	Total kw hr for Private Lighting.	Public Arcs ÷ Total Private Lighting.
1	Berlin .	1 940 000	12 610 000	17 400 000	30 010 000	1 : 15
2	Hamburg .	218 000	483 000	4 890 000	5 373 000	1 : 25
6	Dusseldorf.	161 500	234 500	1 466 000	1 700 500	1 : 10
7	Rotterdam.	61 500	248 500	798 000	1 046 500	1 : 17

Let us estimate the street lighting at 25 per cent. of the interior lighting. Hence for our city of one million inhabitants, we shall require to deliver from the generating station for street lighting

$$11{,}7 \times 0{,}25 = 2{,}9 \text{ million kw hr per year.}$$

TABLE XXV.

Table for Electric Tramways in various British Towns, showing Car Miles per Inhabitant and Kw Hr per Car km. (See next page for text).

No.	Place.	Population in Thousands.	Car Miles per Inhabitant.	Kw Hr per Car Mile.
1	Sheffield	425	21,8	0,99
2	Leeds	446	22,0	0,87
3	Manchester . . .	750	29,5	0,75
4	Liverpool . . .	760	25,8	1,02
5	Glasgow . . .	1000	26,2	0,58
6	Sunderland . . .	159	14,7	0,68
7	Cardiff	108	25,3	1,04
8	Nottingham . . .	240	17,0	0,95
9	Potteries District . .	270	12,4	0,95
10	Warrington . . .	80	8,4	0,73
11	Cork	90	15,8	0,68
12	Oldham	100	22,8	0,95
13	Brighton . . .	123	15,0	0,96
14	Darwen	40	10,1	1,04
15	Carlisle	46	11,7	0,63
16	Burton	52	14,0	0,84
17	Rotherham . . .	58	16,4	1,01
		Average .	18,4	0,87

Surface Tramway Load.—By a similar process of averaging the tramway returns for seventeen cities in England, we find an average of 18,4 car km per year per inhabitant; and an average consumption of 0,87 kw hr per car km. The data is set forth in Table XXV.

For our town of one million persons we should expect about 18,4 million car km per year. On the basis of 0,87 kw hr per car km, we should require $18{,}4 \times 10^6 \times 0{,}87 = 16$ million kw hr per year for surface tramways. Such a city would also require at least some 22 km of double track overhead or underground railway. Taking as a basis the Central London Railway, which, with its 9,25 km, requires annually, including lifts and lighting, some eighteen million kw hr, we should, for our 22 km, require $\frac{22}{9{,}25} \times 18 = 43$ million kw hr per year, for overhead or underground railway.

Power.—From returns of eight large continental towns set forth in Table XXVI. with an average population of about half a million we find the average connection for power works out at 12,5 h p per 1000 inhabitants. Also the mean value for the kw hr consumed per year per connected h p of motive power is 244 kw hr per year for these towns. These figures will of course depend on the nature of the locality and the class of manufacture, but their probable values as set out in Table XXVI. indicate that for our typical town of one million people we shall not err very much during the first years of working in calculating on the mean values obtained.

TABLE XXVI.

Table of Electricity Supply in various Continental Towns showing h p connected in Motors per 1000 Inhabitants, and kw hr per Year per h p connected.

No.	Place.	H p in Motors connected per 1000 Inhabitants.	Kw hr per year per h p connected.	Population in Thousands.
1	Berlin	20,7	516	2835
2	Hamburg	12,4	298	830
3	Breslau	6,5	356	446
4	Bremen	11,7	160	201
5	Dusseldorf	9,1	256	237
6	Rotterdam	14,0	125	370
7	Karlsruhe	18,2	132	106
8	Konigsberg	7,6	312	195
	Average	12,5	244	

Hence for our town of one million inhabitants, the power connection would, on this basis, amount to 12 500 h p of motors, causing $12\,500 \times 244 = 3$ million kw hr per year at the customers' meters, and requiring a supply of $\frac{3}{0{,}85} = 3{,}5$ million kw hr from the generating station. Summing up the various requirements we obtain Table XXVII.

TABLE XXVII.

Total Electricity required for Hypothetical City of 1 000 000 *Inhabitants.*

Employed for	Millions of kw hr required from Generating Station per Year.
Interior Lighting	11,7
Street Lighting	2,9
Surface Tramways	16,0
Elevated or Underground Railways	43,0
Power	3,5
Total	77,1

Statistics show, however, that the use of electricity for lighting, traction and power, is growing rapidly, whereas the above deduced total is based upon present conditions. This consideration makes it necessary to make our plans with a view to increasing the above output by 50 per cent. in the course of, say, the next ten years. Hence we shall design our generating station for an ultimate capacity of $1{,}50 \times 77{,}1 = 116$ million kw hr per year, or say, some 120 million kw hr per year.

At first, however, we shall only purchase generating apparatus sufficient for providing for one-third of the above amount, or 40 million kw hr per year, and we shall thus save the interest on the capital outlay which would be required to install at first sufficient machinery to provide 120 million kw hr.

If our expectations are realised, we shall have sufficient demand for power to justify installing machinery for another forty million kw hr at the end of four years of working and by the end of the eighth year of working, the remaining forty million kw hr will be called for and will justify installing sufficient machinery to bring the station up to the full capacity for which it was originally planned. This procedure also has the advantage that we can obtain, in the second and third groups of machinery, the advantage of

improvements made in the design of generating apparatus during the coming eight years.

Annual Increase in Output.—Table XXVIII. shows the output of nine important provincial towns for the years 1896 and 1906, and the average increase per annum.

TABLE XXVIII.[1]

Showing the Growth of the Demand for Electricity in Nine Provincial Towns.

Town.	Year of Working (1896).	Output in Millions of Kw Hr.		Increase in 10 Years.	Average Increase per Cent. Per Annum.
		1896.	1906.		
Glasgow	4th	1,1	43,9	42,8	44,7 %
Newcastle-on-Tyne	7th	0,9	42,2	41,3	46,7 %
Manchester	2nd	1,8	40,0	38,2	36,8 %
Liverpool	13th	1,2	31,5	30,3	38,8 %
Leeds	2nd	0,5	21,9	21,4	45,3 %
Sheffield	2nd	0,3	16,7	16,4	50,2 %
Bradford	5th	0,7	14,0	13,3	35,5 %
Edinburgh	1st	0,9	12,9	12,0	30,7 %
Salford	1st	0,05	10,9	10,8	70,6 %

Table XXIX. gives the population of these towns for the same years, and the average rate of increase. In Table XXX. is compared the demand for electricity per inhabitant for the two years.

TABLE XXIX.

Showing the Growth of the Population in Nine Provincial Towns.

Town.	Population in Thousands.		Increase in 10 Years.	Average Increase per cent. per Annum.
	1896.	1906.		
Glasgow	817	785	− 32	− 0,5 %
Newcastle-on-Tyne.	197	377	+ 180	+ 7 %
Manchester	520	625	+ 105	+ 2 %
Liverpool	518	704	+ 186	+ 3 %
Leeds	390	463	+ 73	+ 2 %
Sheffield	334	448	+ 114	+ 3 %
Bradford	216	289	+ 73	+ 3 %
Edinburgh	277	337	+ 60	+ 2 %
Salford	198	234	+ 36	+ 3 %

[1] The first four columns of this Table are from page 436 of the *Electrical Times* of September 27th, 1906.

TABLE XXX.

Showing the Demand for Electricity per Inhabitant in Nine Provincial Towns for the Years 1896 and 1906.

Town.	Output in Kw Hr per Inhabitant.		Increase in 10 Years.	Average Increase per cent. per Annum.
	1896.	1906.		
Glasgow . . .	1,4	56,0	54,6	15 %
Newcastle-on-Tyne .	4,6	92,3	87,7	7 %
Manchester . .	3,5	64,0	60,5	6 %
Liverpool . .	2,3	44,7	42,4	7 %
Leeds . . .	1,3	47,4	46,1	14 %
Sheffield . . .	0,9	37,3	36,4	37 %
Bradford . . .	3,2	48,5	45,3	4 %
Edinburgh . .	3,3	38,3	35,0	1,5 %
Salford . . .	2,5	46,5	44,0	6 %

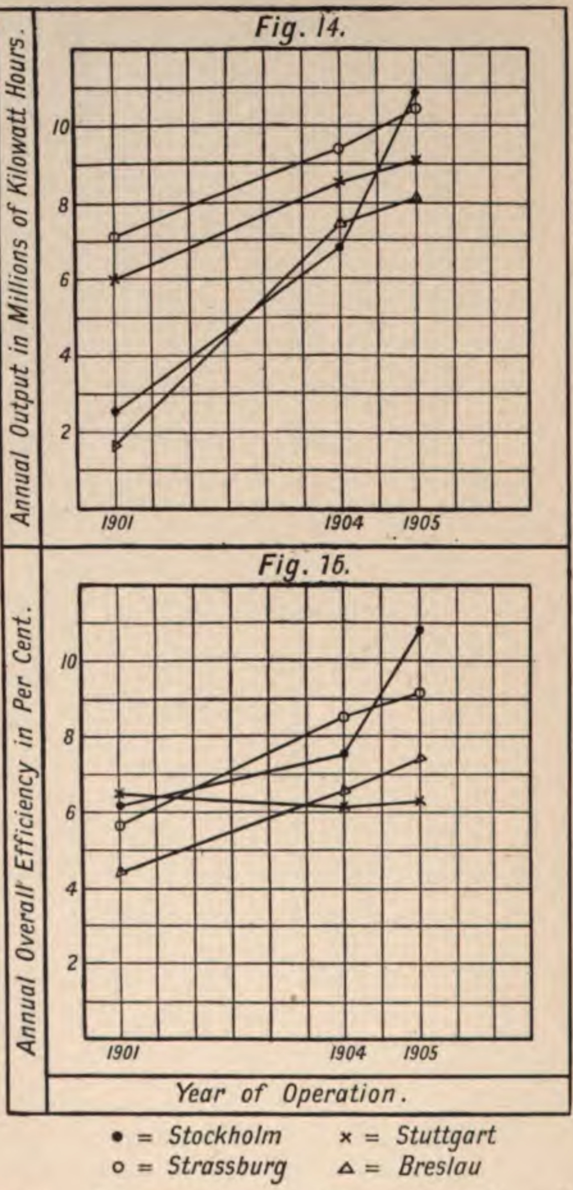
Table XXXI. shows the demand for electricity per inhabitant for 158 continental generating stations.

TABLE XXXI.

The demand for Electricity in 158 Continental Generating Stations.

Number of Stations.	Output in kw hr per Inhabitant.
2	2
5	4
16	6
12	8
16	10
15	12
26	15
13	17
14	20
15	25
10	30
7	35
11	over 35

As to the growth of the demand for electricity in continental towns, Table XXXII shows the electrical output and efficiency of the generating stations in four continental towns for the years 1901, 1904 and 1905. The results are shown in graphical form in Figs. 14 and 15.



Figs. 14 and 15. ANNUAL OUTPUT AND EFFICIENCY OF FOUR CONTINENTAL GENERATING STATIONS.

TABLE XXXII.

Electrical Output and Efficiency of the Generating Stations in Four Continental Towns from 1901—1905.

Town.	1901.		1904.		1905.	
	Output.	Efficiency.	Output.	Efficiency.	Output.	Efficiency.
Stockholm . .	2,6	6,1 %	6,8	7,6 %	10,9	10,4 %
Strassburg . .	7,1	5,7 %	9,4	8,6 %	10,6	9,2 %
Stuttgart . .	6,0	6,5 %	8,5	6,1 %	9,1	6,8 %
Breslau . .	1,7	4,5 %	7,4	6,7 %	8,1	7,6 %
Average . .	4,4	5,7 %	8,0	7,3 %	9,7	8,4 %

In laying down the plans for a generating station it should be borne in mind that as the output of the station increases, the

TABLE XXXIII.

Average Efficiency of Continental Generating Stations of various Outputs for different Years.

Output in Millions of Kw Hr per Year.	Number of Stations.	Efficiency.	Year.
Less than 1	24	4,1	1901
1—5	30	5,6	
6—10	3	6,1	
11—20	5	6,5	
100	1	9,8	
Less than 1	63	6,5	1904
1—5	40	6,1	
6—10	15	7,0	
11—20	8	7,8	
21—50	3	7,5	
51—100	1	5,9	
over 100	1	11,1	
Less than 1	71	6,4	1905
1—5	36	6,1	
6—10	17	7,1	
11—20	11	7,8	
21—50	1	6,9	
51—100	1	11,1	
over 100	1	10,0	

attainable efficiency will increase also. This has already been shown in the case of the four continental towns analysed in Figs. 14 and 15. That it has more general application is indicated by Table XXXIII. which is a summary of the workings of a large number of continental generating stations over a period of five years. Table XXXIII gives the average efficiency of a large number of continental generating stations of different outputs for

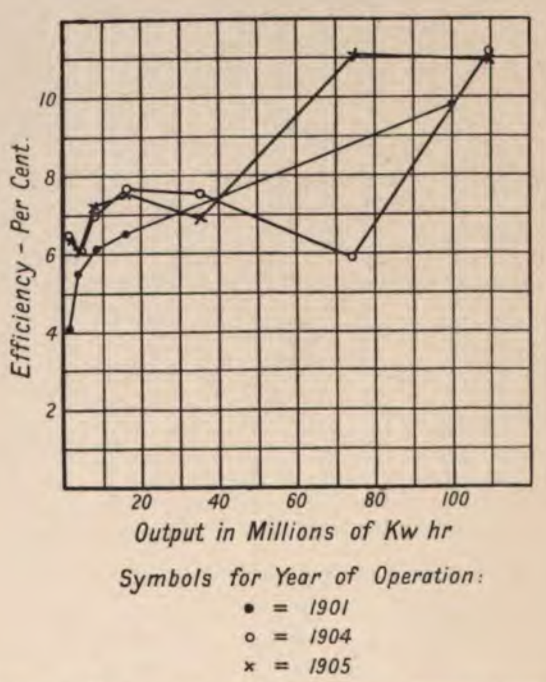


Fig. 16. Average Efficiency of Continental Generating Stations of Various Outputs for Different Years.

various years, and the number of stations analysed. The results are given graphically in Fig. 16.

Another method of investigating the growth of the demand for electricity is to consider the number of kilowatts of rated capacity of the apparatus connected to the distributing mains of the generating station. An investigation into this question has been made by Hoppe, and the present author has put the results into graphical form in Fig. 17. In this figure, the abscissae represent the rated number of kilowatts connected per 1000

inhabitants, and the ordinates the year of operation of the generating station.

Considering the uppermost curve, we see that for eleven towns

Year of Commencem^t	Number of Towns
1893	11
1894	15
1895	22
1896	15
1897	50
1898	50
1899	71
1900	82
1901	44
1902	32

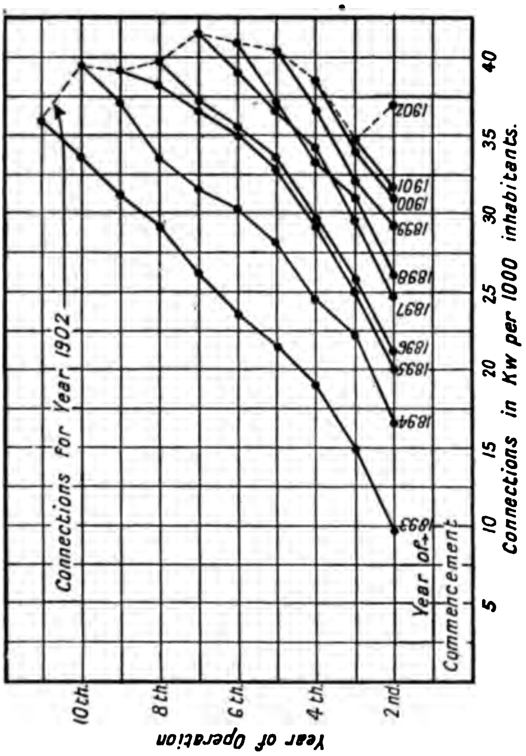


Fig. 17. Average Rated Amount of Connections to the Distributing Mains of Generating Stations of Towns with a Population of under 10,000 Inhabitants.

which started supplying electricity in the year 1893, the rated connections were 10 kw per 1000 inhabitants at the end of the second year of operation, and that they had risen to 36 kw at the end of the eleventh year of operation (1902).

Comparing with this the fact that fifteen towns commenced supply in 1894, the rated kilowatts being seventeen at the end of the second year, and 39,5 at the end of the tenth year, the number of towns starting supply each year is given in the Table at the side of Fig. 17. All the towns under consideration had a population of less than 10 000 inhabitants.

Capacity of Single Generating Station.—As illustrations of the size of modern generating stations, some rough leading data of a number of such stations have been brought together in Table XXXIV.

TABLE XXXIV.

Leading Particulars of three well-known Generating Stations.

Name of Generating Station.	Millions of Kilo-watt-Hours delivered from Generating Station per Year during One Year or Half Year.	Period considered.	Total Kilowatts rated capacity of Generating Sets, excluding Exciters and Sets for Lighting and Power in Generating Station.	Average load during total period considered (based on 24-hour day).	Max. Load during Total Period considered.	Load Factor at outgoing Mains from Generating Stations.
Pinkston Station Glasgow Corporation Tramways	26	Year ending May 1906	11 200	2980	9600	31 %
Shepherd's Bush Station (Central London Railway)	18,1	Half year ending June 30th 1905	5100	2060	4000	52 %
Ringsend Station (Dublin United Tramways)	8,2	Half year ending June 30th 1905	3600	936	—	—

In Table XXXV. are given rough estimates of the ultimate capacities for which these stations would be suitable with a 50 per cent. load factor. To the three stations in Table XXXIV. there have been added in Table XXXV. the Neasden Generating Station of the Metropolitan Railway of London, and the Chelsea (Lot's

Road) Power Station of the Underground Electric Railways Company of London; the estimates in these last two cases are, of course, only of the roughest nature, as although electrical power has now been delivered from these two stations for some considerable time, a number of initial difficulties of various sorts have retarded developments, and have led the interested parties to suppress information.

TABLE XXXV.

Ultimate Capacities of Various Stations for 50 per cent. Load Factor.

Name of Generating Station.	Millions of Kilowatt Hours of Annual Capacity of Generating Station for a 50 per cent. Load Factor.	Total Kilowatts Rated Capacity of Generating Sets excluding Exciters and Sets for Lighting and Power in Generating Station.	Average Load based on a 24-Hours Day.	Corresponding Maximum Load (based on 50 per cent. Load Factor).	Rated capacity of Generating Sets Installed per Million Kw Hr Output per Annum.
Dublin .	13	3600	1480	2960	277
C.L.R. .	19,5	5100	2220	4440	262
Glasgow .	44	11 200	5000	10 000	255
Neasden .	58	14 000	6600	13 200	241
Chelsea .	200	44 000	22 800	45 600	220

Systematic Procedure in the Design of Steam-Driven Electric Generating Stations.—Single generating stations may thus deliver hundreds of millions of kilowatt-hours of electrical energy per annum. Let us roughly work out some preliminary figures for stations of capacities for delivering 10, 30, 90 and 270 millions of kilowatt-hours per annum. By reference to Table XXXV. we see that while for the smaller of these stations we shall require to install generating sets having 280 kw rated capacity per million kw hr per annum, the largest station will require but 200 kw rated capacity per million kw hr per annum. The total rated capacity of generating sets to be installed, the number of sets and the rated capacity per set, are set forth in Table XXXVI.

With steam generating sets, practically as low a rate of steam consumption has been obtained with 1800 kw sets as with any of larger capacity. Hence for all but the smallest one of these four stations, we can estimate on obtaining the same average steam consumption. Taking an absolute admission pressure of 13 kg per

TABLE XXXVI.

Particulars of Generating Sets to be Installed.

Designation of Generating Station.	Millions of Kw Hr per Annum.	Rated Capacity of Generating Sets per Million Kw Hr per Annum, for 50 per cent. Load Factor.	Kilowatts Total Rated Capacity of Generating Sets to be Installed.	No. of Generating Sets to be Installed.	Kilowatts Rated Capacity of each Generating Set.
A	10	280	2800	4	700
B	30	240	7200	4	1800
C	90	210	18 900	4	4700
D	270	200	54 000	8	6800

sq cm, 50° C of superheat, and an exhaust pressure of 0,15 kg per sq cm, a fair figure for the "all-day" steam consumption of the 700 kw sets will be 8,9 kg per kw hr, and for the larger sets, 8,4 kg per kw hr, as in Table XXXVII.

TABLE XXXVII.

Representative Values of Steam Consumption of Generating Sets.

Rated Output in Kw.	Steam Consumption at Rated Load.	"All day" Steam Consumption.
700	8,0	8,9
1800	7,5	8,4
4700	7,5	8,4
6800	7,5	8,4

The next steps in the estimate are set forth in Table XXXVIII.

TABLE XXXVIII.

Particulars of Steam Consumption for Stations of Various Capacities.

Designation of Generating Station.	Capacity in Millions of Kw Hr per annum.	Steam Consumption in Kg per Kw Hr.	Tons of Steam Consumed per annum.	Average Tons of Steam per Hour during year.
A	10	8,9	89 000	10,2
B	30	8,4	252 000	28,8
C	90	8,4	756 000	86,4
D	270	8,4	2 268 000	259

The next step is to work back from the steam to the coal. Table III. sets forth the energy in kilowatt hours required to raise

one ton of steam of various pressures and superheats. From this Table we find that for our standard conditions of pressure and superheat (13 kg per sq cm and 50° C superheat) 810 kw hr of energy are expended in raising one ton of steam from one ton of water at 0° C. But we may take the temperature of the feed water as 50° C since we are able to re-employ the heat in the condensed steam to raise the temperature of the feed water.

From Table I. on p. 4 we find that 58 kw hr are required to raise one ton of water from 0° C to 50° C. Hence to obtain one ton of steam at our standard conditions of pressure and superheat, from feed water at 50° C, we shall require to impart to the steam—

$$810 - 58 = 752 \text{ kw hr.}$$

The average boiler efficiency will be to a considerable extent dependent upon the size of the station, because the larger the station the smaller is the percentage of boilers in operation at less than full load. Hence we shall for our four plants take the average boiler efficiency for the year at

66, 68, 70, and 71 per cent. respectively.

Taking 5 per cent. loss in the steam piping for all cases, we have for the combined efficiency of boilers and steam piping:

63, 65, 67, and 68 per cent.

Thus we must burn under the boiler a fuel of such quality and amount as to provide during the year the energy of combustion shown in the last two columns of Table XXXIX.

TABLE XXXIX.

Particulars of Energy contained in Steam used by Generating Sets Installed in Stations in Table XXXVIII.

Designation of Station.	Capacity in Millions of Kw Hr per Annum.	Tons of Steam Consumed by Generating Sets per Annum.	Energy in Kw Hr to be given to each Ton of Steam.	Total Energy to be Imparted to Steam per Year in Millions of Kw Hr.	Combined Efficiency of Boilers and Steam Piping.	Total Energy of Combustion in Millions of Kw Hr per Annum.	Total Energy of Combustion per hour during Year in Kw Hr.
A	10	89 000	752	67	63 %	105	12 160
B	30	252 000	752	190	65 %	292	33 400
C	90	756 000	752	570	67 %	850	97 200
D	270	2 268 000	752	1710	68 %	2520	288 000

From the data in Table XXXIX., we may obtain the annual overall efficiency of these generating stations, as shown in Table XL.

TABLE XL.

Annual Overall Efficiencies of the Generating Stations given in Table XXXIX.

Designation of Generating Station.	Capacity in Millions of Kw Hr Delivered from Station per Annum (S).	Total Energy of Combustion of Coal Burned in Millions of Kw Hr per Annum (T).	Annual Overall Efficiency of Generating Station $\frac{100\,S}{T}$
A	10	105	9,5%
B	30	292	10,3%
C	90	850	10,6%
D	270	2520	10,7%

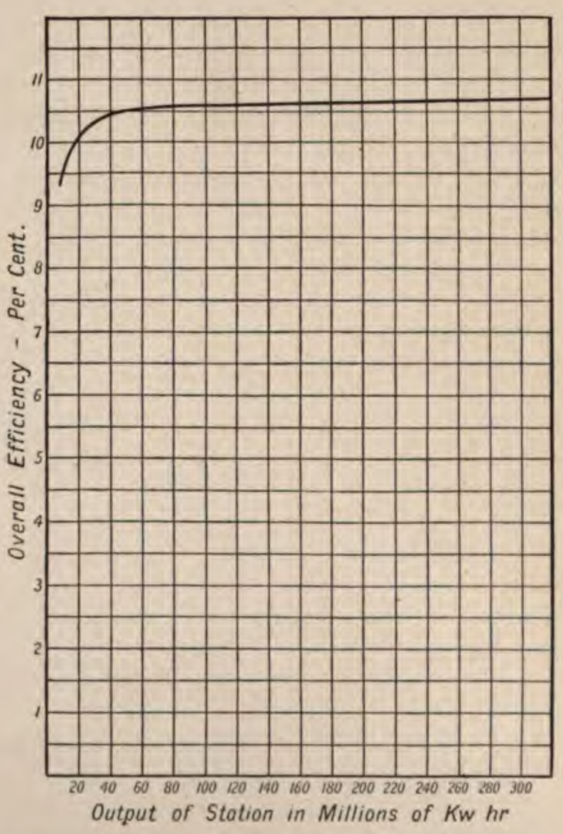


Fig. 18. ESTIMATED EFFICIENCIES OF STATIONS OF VARIOUS CAPACITIES. From Table XL.

From the curves in Fig. 8 we have seen that the average annual overall efficiencies obtained in practice, on plants of 10 and 30 millions of kw hr of annual capacity, are 7,3 per cent. and 8,4 per cent. respectively, as against the above estimated figures of 9,5 and 10,3.

$$\frac{9{,}5}{7{,}3} = 1{,}30 \qquad \frac{10{,}3}{8{,}4} = 1{,}23.$$

As our assumptions in developing the estimates for these four stations have been very conservative, we may say that it would be reasonable to attempt to improve average present practice, as indicated by the curve in Fig. 8, by at least 30 per cent. in stations of 10 million kw hr of annual output, and by some 25 per cent. in stations of 30 million kw hr of annual output.

The results for the annual overall efficiency as arrived at in the last column of Table XL. are plotted in Fig. 18.

Returning to our estimates, let us assume that we employ a quality of coal with a calorific value of 8700 kw hr per ton. From this figure we at once obtain the number of tons of coal burned per year, as set forth in Table XLI.

TABLE XLI.

Coal Consumption for Stations A, B, C and D.

Designation of Station.	Capacity in Millions of Kw Hr per annum.	Total energy of combustion per annum in Millions of Kw Hr.	Energy of Combustion of one Ton of Coal.	Tons of Coal Consumed per year.	Do. per hour (Average for Year).
A	10	105	8700	12 100	1,38
B	30	292	8700	33 600	3,84
C	90	850	8700	97 700	11,1
D	270	2520	8700	290 000	33,2

TABLE XLII.

Coal Consumption in Kg per Kw Hr for Stations A, B, C and D.

Designation of Station.	Capacity in Millions of Kw Hr Delivered from Generating Station per Annum.	Tons of Coal Burned per Annum.	Kg of Coal Burned per Kw Hr Delivered.
A	10	12 100	1,21
B	30	33 600	1,12
C	90	97 700	1,08
D	270	290 000	1,07

In Table XLII. are derived results for the kilograms of coal burned (of a calorific value of 8700 kw hr per ton) per kw hr of electrical energy delivered from the generating station per annum.

Following these rough preliminary estimates of the quantities involved, the design of coal bunkers, coal conveyors, boilers, superheaters, condensing plant, piping, generating sets, cables and switchboard, all require detailed consideration. The purpose of the present chapter, however, has been to lay down a systematic plan of procedure in the choice of plant of the type indicated.

CHAPTER III

STEAM RAISING PLANT

In the preceding chapter we derived fair values for the steam consumption of generating stations of various sizes.

For an absolute admission pressure of 13 kg per sq cm, 50° C of superheat and an exhaust pressure of 0,15 kg per sq cm, we arrived at certain values for the steam consumption for stations with a 50 per cent. load factor. These values, which should be attainable in well-designed plants, are given again in Table XLIII.

TABLE XLIII.

Annual and Hourly Steam Consumption of Large Electric Generating Stations.

Capacity of Station in Millions of Kilowatt Hours per annum.	"All Day" Steam Consumption in Kilograms per Kilowatt Hour.	Tons of Steam Consumed per annum.	Average Tons of Steam per Hour during Year. (There are 365 × 24 = 8750 hours in one year.)
10	8,9	89 000	10,2
30	8,4	252 000	28,8
90	8,4	756 000	86,5
270	8,4	2 270 000	259

Thus, on the assumption that the maximum load is occasionally of one hour's duration, we have

TABLE XLIV.

Maximum Hourly Steam Consumption of Large Electric Generating Stations.

Capacity of Station in Millions of Kilowatt Hours per annum (50 per cent. Load Factor).	Average Tons of Steam per hour during Year.	Maximum Tons of Steam per hour.
10	10,2	20,4
30	28,8	57,6
90	86,5	173
270	259	518

Table XLIV. shows that, for a generating station of 270 million kw hr capacity per year, the aggregate boiler plant must have sufficient capacity, including a reasonable provision for spare plant, to deal with 518 tons of steam per hour.

For high speed generating sets, whether reciprocating or turbine sets, the size of the required engine room is very small in comparison with the size of the boiler house, and it becomes a serious problem to avoid great lengths of steam piping from the boilers to the generating sets.

In Fig. 19 is shown a diagrammatic section of a typical electricity station with slow speed vertical engines. In this case the engine

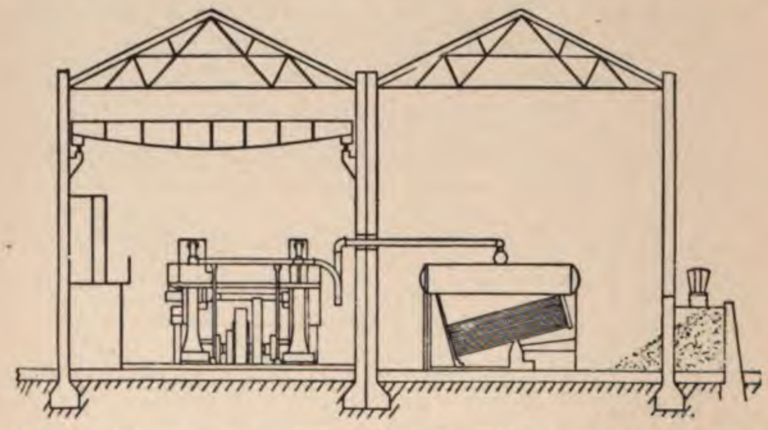


Fig. 19. DIAGRAMMATIC SECTION OF A TYPICAL POWER STATION, WITH SLOW SPEED VERTICAL ENGINES.

room and the boiler house are of about the same size. This outline should be compared with the outline of the steam turbine station shown in Fig. 21, from which it will be seen that the space occupied by the boiler house is several times that occupied by the engine room. (This subject is further dealt with in Chapter VII.).

Hence the space occupied by boilers is an important consideration, and is leading to the very general use of boilers of the water-tube type. One of the most notable features of this type of boiler is its economy in floor space as compared with other types. It may be said that for large generating stations, some type of water-tube boiler is generally preferable.

In Table LVI. of Chapter VII. are given leading particulars of the boiler plant in a number of modern generating stations. For a

given required total boiler capacity, the greater the capacity of the individual boiler the less will be the total space occupied by the boiler installation. The manufacturers of the leading types of water-tube boilers are prepared to deliver as standard apparatus boilers with a normal evaporative capacity of 15 tons per hour "from and at" 100° C. Table III. on p. 8 shows that to evaporate one ton of water at atmospheric pressure and consequently at a temperature of 100° C into steam at the same temperature and pressure, requires the absorption by the ton of water, of

626 kw hr of energy.

Hence this boiler, which the makers are rating at a normal capacity of 15 tons per hour "from and at" 100° C, is one capable, at normal load, of conveying to the interior of the boiler

$$15 \times 626 = 9400 \text{ kw hr of energy per hour,}$$

i.e., at its normal rate of working, it is a 9400 kw boiler. In general, the better the quality of the coal the more may be gotten out of a boiler of a given rated capacity, although the variation in the steam raising capacity due to variations in the quality of the coal is of very limited range.

Thus we may state that this standard boiler is a boiler with which energy may be conveyed to the contents at the rate of

9400 kw.

If it is required in such a boiler to raise steam at an absolute pressure of 13 kg per sq cm from water at 50° C, and to superheat the steam by 50° C, then we find from Table III. (on p. 8) that $810 - 58 = 752$ kw hr must be imparted to each ton of water in the boiler.

Thus, under these conditions, we can, as normal load, only produce

$$\frac{9400}{752} = 12{,}5 \text{ tons of steam per hour.}$$

With an absolute pressure of 18 kg per sq cm, and with 150° C of superheat,

$$\frac{9400}{878-58} = 11{,}5 \text{ tons of steam per hour}$$

will be produced at normal load.

This way of treating the matter is to a certain extent faulty, since the tubes devoted to superheating purposes are generally located at a remote part of the boiler only accessible to the hot products of combustion after these have already circulated amongst the tubes in which the water is evaporated, and the effect is more or less confined to reducing the temperature of the flue gases. When,

however, the superheater is built into the boiler, it is difficult to establish any hard and fast line of demarcation, and we shall be on the safe side in handling the question as above indicated.

Now, in our 270 million kw hr per year station, we have arranged to employ eight main generating sets, each of a rated capacity of 6800 kw. When running at rated load with a steam pressure of 13 kg per sq cm, and with 50° of superheat, the steam consumption (with an exhaust pressure of 0,15 kg per sq cm) is 7,5 kg per kw hr (see Fig. 45, Chapter IV.), or a total consumption of

$$6800 \times 0{,}0075 = 51 \text{ tons of steam per hour.}$$

We have seen that under these conditions, one of the boilers, when working at its rated capacity, delivers 12,5 tons of steam per hour.

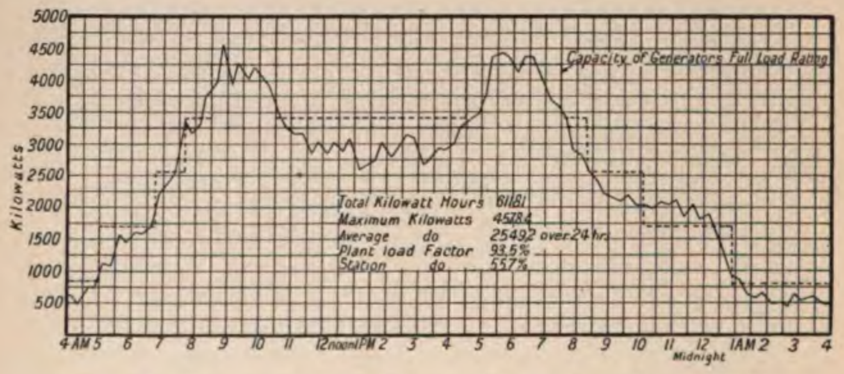


Fig. 20. Central London Railway Daily Load Curve, 1906.

Now, although the load factor of the whole station is 50 per cent. for the year, it is important to have each generating set and its group of boilers running as close as practicable to its rated capacity. When actually running at the rated capacity, we have 100 per cent. "plant" load factor. Above the rated capacity we may or may not have higher efficiency; but we should, in any case, only consider running above rated capacity as in the nature of an overload, and only permissible for reasonably short periods, say, at the most, a couple of hours. The preferable adjustment is such that the average of the fluctuating load shall be approximately the rated load. Thus, in the case of the Central London Railway, the load during the 24 hours varies as shown in Fig. 20, and, as indicated on the diagram, arrangements are made to vary the number of generating sets in service so as to obtain nearly 100 per cent.

"plant" load factor, although the "station" load factor for the year is only about 55 per cent.

If we install four of these standard 9400 kw boilers for each generating set, we shall, at rated load, require to work each boiler at $\frac{51}{4} = 12{,}8$ tons of steam per hour, which, for a boiler pressure of 13 kg and for 50° C of superheat, is only about 2 per cent. overload. Thus as we have eight generating sets we must install

$$4 \times 8 = 32 \text{ boilers.}$$

The precise arrangement of the boilers is a matter of the design of the station as a whole, which is carried further in Chapter VII. Let us for the present consider a single 6800 kw generating set and its group of four 9400 kw boilers.

It is of course desirable to arrange the boilers at as small a distance from the generating set as other conditions render practicable, in order to reduce both the cost and the length of the piping. In Table XLV. are brought together for Lot's Road, Neasden, and Central London, the average length of the steam pipe connection from the boilers to the particular generating set which they are designed to supply when normally operated.

TABLE XLV.

Length of Steam Piping in Large Electric Generating Stations.

Station.	Average Length of Steam Piping to Engine or Turbine, in Meters.
Lot's Rd., Chelsea . .	43
Neasden	37
Central London Railway .	55
Average value . .	45 meters

We see that it is frequently necessary that this distance shall be some 45 meters. The distance is generally greater in large than in small plants.

In Fig. 21 is indicated a general outline of the design for the 270 million kw hr per annum station, having eight 6800 kw turbo sets and four boilers for each set. This drawing gives a good idea of the relative space required by engines and boilers, and the great

length of steam piping required between one turbine and its boilers. We shall shortly take up the question of the general design of the steam piping.

First, however, let us take up certain questions relating to the boiler. Boilers of this type and capacity should have a **heating surface of 7 sq dm per kw rated capacity of the boiler**; hence a total heating surface of 66 000 sq dm per boiler.

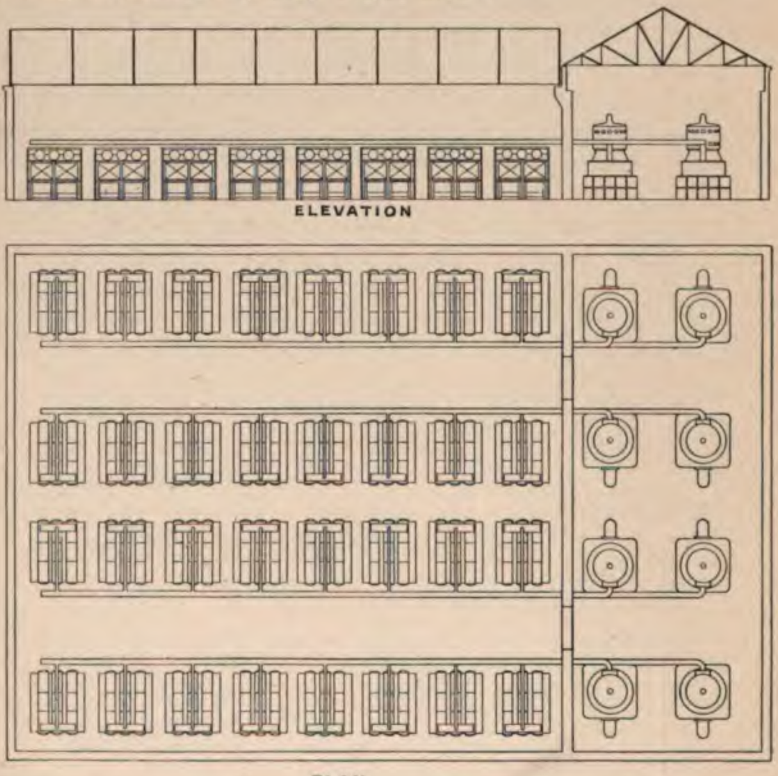


Fig. 21. General Outline of Preliminary Design for Large Steam Turbine Generating Station.

When burning bituminous coal of a calorific value of 8700 kw hr per ton, suitably fired and with a suitable air supply, these boilers should show an efficiency of 70 per cent. Thus coal with a total calorific value of

$$\frac{9400}{0{,}70} = 13\ 400 \text{ kw hr}$$

must be burned per hour under each boiler.

This amounts to

$$\frac{13\ 400}{8700} = 1{,}54 \text{ tons per hour.}$$

For burning this grade of coal, the boilers should be provided with a **grate surface of 0,09 sq dm per kw hr of calorific capacity.** The total grate surface per boiler should thus be $0{,}09 \times 13\ 400 = 1210$ sq dm corresponding to 1,27 kg of coal per sq dm per hour.

A grate for hand firing should be some 10 per cent. larger, thus running to 0,10 sq dm per kw hr of calorific capacity, and being

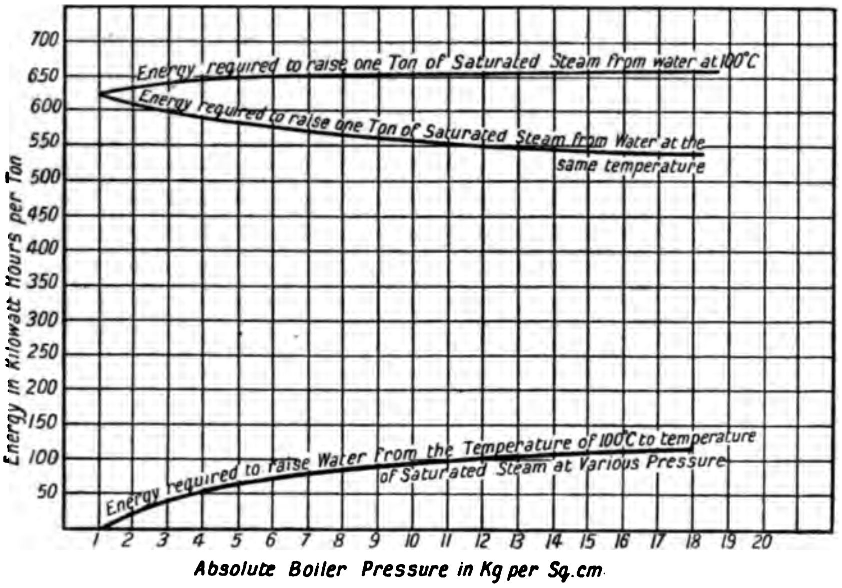


Fig. 22. Curves of Water Heat, Latent Heat and Total Steam Heat.

suitable for burning only some 1,15 kg of coal per sq dm per hour.

Present developments in boiler construction do not justify considering as standardised, boilers of larger rated capacity than the size here discussed, although it is to be hoped that progress will soon be made in the development of boilers of much larger capacity. Let us assume that this standard boiler is supplied with a chain grate stoker designed for burning a good quality of bituminous coal of an average calorific capacity of 8700 kw hr per ton. If we provide independently fired superheaters, and also preheating apparatus,

so that the function of the boiler shall be restricted chiefly to evaporating water already heated to the boiling point corresponding to the boiler pressure, the calculations for the boiler itself must be correspondingly modified.

The first function, pre-heating, relieves the boiler of but a small percentage of its duty. Much the greater portion of the boiler's duty relates to converting the water into steam. The relative amounts required for these purposes when a boiler of this standard type is working at its rated capacity may, for various pressures, be taken at the values plotted in Fig. 22.

The Economic Pressure.—One of the first questions to be decided in the design of a steam driven generating station relates to the economic steam pressure. When other considerations require that piston engines shall be employed, it will be necessary, in the interests of good economy, to install high pressure boilers, for the economy of piston engines increases markedly with increasing steam pressures. Out of consideration for this fact, steam pressures have gradually been increased, until, in recent installations, specific pressures of less than 12 kg have been very exceptional, and it has been considered good practice to employ considerably higher specific pressures, up to 16 kg or more.

In a subsequent chapter dealing with piston engines and turbines, it will, however, be shown that while, as just stated, the economy of piston engines is distinctly improved with increasing steam pressures, there is, in the case of steam turbines, comparatively very slight improvement with increasing pressure, so slight indeed that it does not justify sacrificing other advantages. In fact, it becomes of distinct economic advantage, when turbines are employed, to adopt much lower boiler pressures. This largely rests upon the consideration that the lower the boiler pressure, the greater may be the number of degrees by which the steam may be heated above the temperature of dry saturated steam for a given pressure, without exceeding practicable limits of final temperature. The use of superheated steam has only become at all customary during the last few years. Prior to that time, the temperatures associated with saturated steam had alone to be considered, and thus, even with the increasing boiler pressures which were becoming customary, no prohibitive steam temperatures were reached. When, however, it became apparent that further great economies were possible by the use of superheated steam, engineers were already so far committed and accustomed to the advocacy of high pressures, that they were

disinclined to revert to lower steam pressures. Consequently it became necessary to attack the problems associated with the use of very considerably higher steam *temperatures* than had heretofore been employed. To the already high temperatures associated with saturated steam of high pressure, it was necessary to add the 50° C or more of superheat which was known to be accompanied with considerable further economies.

The construction of superheaters to withstand these high

TABLE XLVI.

Absolute Temperatures of Steam at various Pressures and with various Degrees of Superheat.

Absolute Pressure in Kg per Sq Cm.	Final Temperature of Steam, in Degrees Centigrade, for following Amounts of Superheat.											
	0° C.	10° C.	20° C.	30° C.	40° C.	50° C.	60° C.	80° C.	100° C.	125° C.	150° C.	200 °C.
1	100	110	120	130	140	150	160	180	200	225	250	300
2	120	130	140	150	160	170	180	200	220	245	270	320
3	133	143	153	163	173	183	193	213	233	258	283	333
4	143	153	163	173	183	193	203	223	243	268	293	343
5	151	161	171	181	191	201	211	231	251	276	301	351
6	158	168	178	188	198	208	218	238	258	283	308	358
7	164	174	184	194	204	214	224	244	264	289	314	364
8	169	179	189	199	209	219	229	249	269	294	319	369
9	174	184	194	204	214	224	234	254	274	299	324	374
10	179	189	199	209	219	229	239	259	279	304	329	379
11	183	193	203	213	223	233	243	263	283	308	333	383
12	187	197	207	217	227	237	247	267	287	312	337	387
13	191	201	211	221	231	241	251	271	291	316	341	391
14	194	204	214	224	234	244	254	274	294	319	344	394
15	197	207	217	227	237	247	257	277	297	322	347	397
16	200	210	220	230	240	250	260	280	300	325	350	400
17	203	213	223	233	243	253	263	283	303	328	353	403
18	206	216	226	236	246	256	266	286	306	331	356	406
19	209	219	229	239	249	259	269	289	309	334	359	409
20	212	222	232	242	252	262	272	292	312	337	362	412

temperatures, and the obtaining of cylinder oil which would not be deleteriously affected at these temperatures, presented very grave difficulties for a long time, and even at present these considerations play the major part in limiting the extent to which engineers are inclined to resort to superheating. It is highly improbable that it is even now at all widely realised that the economy of steam turbines is but very slightly improved with increasing steam pressure. It is, however, generally recognised that the economy of all types of engines is considerably improved with an increasing amount of superheat.

When both these facts are clearly appreciated, engineers cannot logically do otherwise than revert to considerably lower steam pressures when turbines are employed as prime movers, for with lower boiler pressures a greater number of degrees of superheat will be associated with a given ultimate steam temperature than with high steam pressures. It is evident that from most standpoints it is the actual temperature of the steam which determines the practicability of employing a given number of degrees of

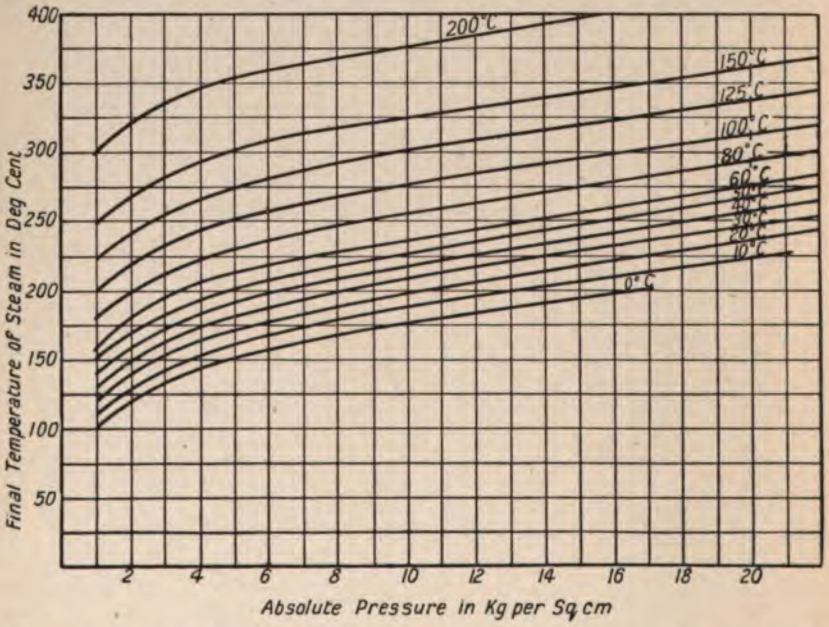


Fig. 23. Curves showing Variation of Final Temperature of Steam with Absolute Pressure and for Various Numbers of Degrees of Superheat.

superheat and of obtaining the corresponding decrease in steam consumption. These considerations will be better appreciated by a study of Tables XLVI. and XLVII. In Table XLVI. are given, for various pressures, the absolute temperatures of steam with various amounts of superheat. While but little interest attaches to Table XLVI., the values in Table XLVII., which is readily compiled from Table XLVI., are of very considerable importance. In Table XLVII. are recorded the absolute pressures corresponding to various amounts of superheat and various steam temperatures. The results in Table XLVI. have been plotted in the curves of Fig. 23.

The progress in the development of superheaters has reached such a point that there is no insurmountable difficulty in dealing with steam temperatures of, say, 300° C. Nevertheless much greater freedom from difficulties will be secured by limiting the steam temperature to 250° C. From Fig. 23 we see that if we employ so high a pressure as 16 kg per sq cm we may give the steam 50° of superheat for a steam temperature of 250° C. If, however, we were to reduce the steam pressure to 8 kg per sq cm,

TABLE XLVII.

Absolute Pressure of Steam in Kg per Sq Cm for various Final Temperatures and Degrees of Superheat.

Final Temperature of Steam in Degrees Centigrade.	Absolute Pressure in Kg per Sq Cm for following Amounts of Superheat.											
	0° C.	10° C.	20° C.	30° C.	40° C.	50° C.	60° C.	80° C.	100° C.	120° C.	150° C.	200° C.
100	1											
110	1,5	1										
120	2	1,5	1									
130	2,65	2	1,5	1								
140	3,6	2,8	2	1,5	1							
150	4,9	3,6	2,8	2	1,5	1						
160	6,2	4,8	3,6	2,8	2	1,5	1					
180	10,2	8,0	6,4	4,8	2,8	2	2	1				
200	16	12,8	10,2	8,0	6,2	2,8	3,6	2	1			
220		19,6	16	12,2	10,2	8,0	6,2	3,6	2	1		
240			22	19,6	16	13	10,2	6,2	3,6	1,7		
200						19,6	16	10,2	6,2	3,3	1,4	
280							22	16	10,2	5,4	2,7	
300								22	16	9,2	4,3	1
320									22	14,4	8,1	2
340										20,6	13,1	3,6
360											18,9	6,2
380												10,2
400												16

the curves of Fig. 23 show us that a superheat of 80° C gives the same steam temperature, namely 250° C. Thus to compare the relative advantages of using pressures of 16 or of 8 kg per sq cm, the relative economies at 16 kg per sq cm and a superheat of 50° C on the one hand, and 8 kg per sq cm and a superheat of 80° C on the other hand, must be compared. This comparison cannot properly be carried out until we have considered the laws controlling the variation of economy with the pressure and the superheat. These are taken up in Chapter IV. For our present purposes we must anticipate, and state that if it is a case of using

steam turbines, the steam consumption is about the same in the two cases, when associated with the use of a reasonably low exhaust pressure, say a pressure of 0,15 kg per sq cm.

This being the case, the next question to be considered relates to the relative costs of steam raising plant for these two pressures. It would appear that the cost of the boilers will be slightly less for the lower pressure, but probably not to a greater extent than to offset the cost of providing the increased superheater surface.

To raise one ton of steam to a specific pressure of 16 kg and 50° C superheat on the one hand, and to 8 kg and 80° C superheat on the other hand, and in both cases from feed water at 50°,

TABLE XLVIII.

Data of Steam Piping.

Name of Generating Station.	Capacity of one Group of Boilers Feeding Main Header, in Tons per Hour.	Diameter of Main Header cms.	Tons of Steam per hr per sq dm of Cross Section of Main Header.	Tons of Steam per hr required by one Engine.	Diameter of Engine Steam Pipe cms.	Tons of Steam per hr per sq dm of Engine Steam Pipe.	Boiler Pressure kgs per sq cm.
Glasgow .	36,4	40,5	2,76	19	35,5	1,92	11
Chelsea .	62,0			53	35,5	5,35	12
C.L.R. .	10,9	30,4	1,5	8	20,3	2,48	11
Greenwich	44,4	30,4	6,12	26,2	30,4	9,7	14
Neasden .				27	25,4	5,4	12

requires respectively 755 and 762 kw hr per ton, or a difference of only 1 per cent.

The chief remaining element to be considered relates to the relative cost of the steam piping in the two cases. We have seen that a length of some 45 meters is a fair average value. In Table XLVIII. are brought together data relative to the cross section of piping employed with boilers of various capacities and pressures.

It is evident from the above table that practice as regards steam piping varies very widely. For a pressure of some 11 to 13 atmospheres, a flow of 5 tons of steam per hr per sq dm section, or a section of about 0,2 sq dm per ton of steam per hour, may be taken as good practice. It is undesirable to have too large a pipe, since not only is the cost greater, but also the radiating surface.

The 6800 kw turbine with which we are dealing is fed from four boilers at a distance of 45 meters from the turbine, and we require

51 tons of steam per hour. There should be provided a steam pipe with

$$0{,}2 \times 51 = 10{,}2 \text{ sq dm}$$

cross section. This has a diameter of 35,6 cm and a periphery of 112 cm. The radiating surface for a length of 45 meters is thus equal to

$$450 \times 11{,}2 = 5100 \text{ sq dm.}$$

The loss from uncovered steam pipes amounts to some 0,17 watts per sq dm surface per degree cent. difference of temperature between the steam temperature inside the pipes and the temperature of the surrounding atmosphere. In the case with which we are dealing the steam temperature is 250° C, or some 225° C higher than the temperature of the air. There is thus a loss of about $225 \times 0{,}17 = 38$ watts per sq dm of pipe surface; and hence a total loss of

$$0{,}038 \times 5100 = 194 \text{ kw.}$$

This amount may be reduced to one quarter or less by suitably covering the pipes. Thus the loss becomes about 50 kw.

As the total energy in the steam delivered from the boilers when the turbo-generator is operating at its rated load is

$$37600 \text{ kw,}$$

the loss by waste from the piping is in this case a negligible amount. Even at one-tenth load it would only be a matter of from 1 to 2 per cent. for covered pipes, rising to some 5 per cent. for bare pipes. Hence our earlier estimate of 95 per cent. for "efficiency of steam piping" is shown to be very conservative for large plants.

The interesting question arises whether the practice of covering pipes with insulating material is of material importance in so many cases as is generally assumed. It is in general the more important the smaller the capacity of the plant.

We are not much concerned with the loss of pressure due to friction of the steam in flowing through the steam pipe, so long as it is of limited amount, since the energy of friction is heat energy and remains in the steam. Thus the loss in pressure tends to produce a rise in temperature.

At a specific pressure of 14 kg and a superheat of 50° a drop of specific pressure of 0,1 kg may be taken for each 40 meters length of straight piping. Bends greatly increase this amount, and precise estimates are impracticable. With carefully designed piping with few bends, and these of large radius, the "equivalent" length should not more than double the actual length. Thus in the case in question the "equivalent" length may be taken as some

90 meters, and the loss in specific pressure would amount to some 0,2 kg.

In practice it is found that the quantity of steam that can be transmitted by a pipe of a given diameter does not vary much with quite considerable variations in pressure and superheat.

The curves of Fig. 24 give values for the amount of steam which can be transmitted in tons per hour, at a specific pressure of 14 kg in pipes of various diameters. The curves are plotted on the basis of a drop in pressure of 0,1 kg per sq cm for a length of

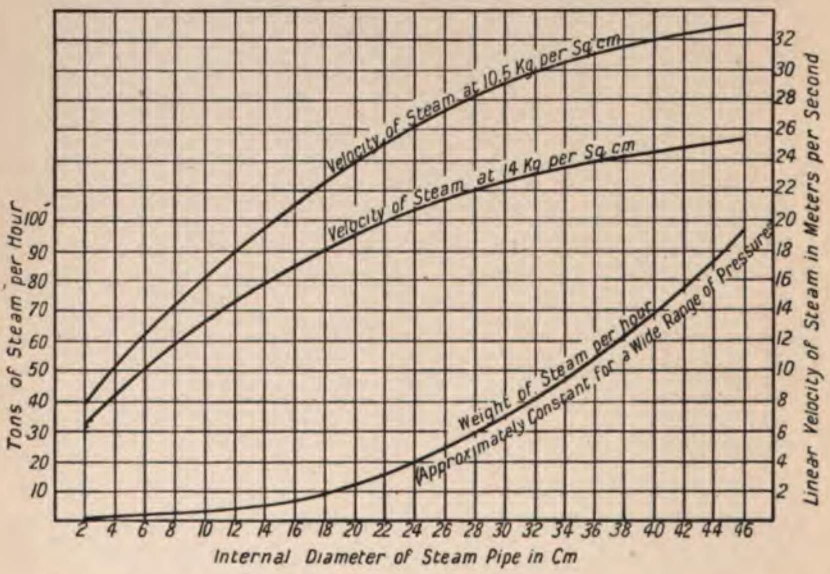


Fig. 24.—Showing the Size of Steam Pipes required for different Weights of Steam.

40 meters. The upper curve gives the velocities corresponding respectively to pressures of 10,5 and 14 kg, for pipes of the diameters defined by the abscissae, and transmitting per hour the amounts of steam corresponding to the lower curve on the sheet. The steam at the lower pressure must of course have the higher velocity since the density, *i.e.*, the weight per unit volume, is less. Now the friction is a function both of the density and the velocity, and these so nearly offset one another as to render it needless to use much if any larger pipes for transmitting the same quantity of steam at lower pressures.

For pipes of a given diameter, the lower pressures would tend towards lower cost. Thus from every standpoint we see that with steam turbines we may employ lower pressures with equal operating costs, and with probably some slight saving in capital outlay. This is, of course, not the case when piston engines are employed, for then the steam consumption rapidly increases with decreasing working pressure.

The rough values of the temperature of the flue gases, as set forth in the following table, are of interest :—

TABLE XLIX.

Rough Values of the Temperature of the Flue Gases in their Passage from Grate to Chimney.

Gases Leaving	Temperature in Degs Cent.
Grate . .	1300
Boiler . .	250 to 350
Economiser .	150 to 200

In the following table are set forth the rates of transference of heat under various conditions :—

TABLE L.

Heat Conduction Values.

Conditions.	Rate of Transference in Watts per Degree Centigrade per sq Decimeter of Heating Surface.
Boiler tubes with feed water at 50° C .	0,2
Boiler tubes with feed water at 150° C .	0,3
Superheater tubes	0,04

In the boiler which we have considered, energy is conveyed to the interior of the boiler at the rate of 9400 kw. Let us take the temperature of the furnace gases as they leave the grate at 1300°, and at 300° on leaving the boiler tubes. The mean temperature is thus 800°. Let us take the feed-water temperature at 50°, and—in the case with a pressure of 8 kg per sq cm—the steam temperature at 170°. Thus the mean temperature is 110°. This gives us a

mean difference of temperature between flue gases and boiler tube contents of some 700°, and the rate of transference of heat may be taken as $700 \times 0{,}2 = 140$ watts per sq dm of tube surface.

For the case of steam at a pressure of 8 kg per sq cm, superheated 80°, we have seen that the heat required to raise one ton of steam from feed-water at 50° is 762 kw hr. Now the heat required for saturated steam at the same pressure is 712 kw hr, so that

$$\frac{712}{762} \times 100 = 93 \text{ per cent.}$$

of the total energy conveyed to the interior of the boiler is devoted to heating the feed-water and evaporating it into steam.

This is

$$9400 \times 0{,}93 = 8750 \text{ kw.}$$

Hence we require

$$\frac{8\,750\,000}{140} = 62\,500 \text{ sq dm of boiler tube heating surface.}$$

Now let us estimate the amount of superheater surface required. This must be sufficient to transfer heat at the rate of 650 kw. The mean temperature of the steam in the superheating tubes is

$$170 + \frac{80}{2} = 210°.$$

Thus the difference of temperature between the mean temperature of the flue gases (800°) and the mean temperature of the contents of the superheater tubes is about 600°, and the transference of heat is at the rate of

$$600 \times 0{,}04 = 24 \text{ watts per sq dm.}$$

We shall thus require

$$\frac{650\,000}{24} = 27\,000 \text{ sq dm of superheater tube surface.}^{1}$$

SUMMARY.

Boiler tube surface	=	62 500 sq dm.
Superheater tube surface . .	=	27 000 ,,
Grate surface	=	1210 ,,

[1] The large amount of surface required for superheaters has in some instances led to the use of corrugated tubes in order to reduce the size and cost of the apparatus.

CHAPTER IV

PISTON ENGINES AND STEAM TURBINES

FOR electric generating stations, steam-turbine-driven generating sets are becoming more and more frequently employed, and there is every indication that the piston engine will gradually be superseded for large units.

Although there are still a good many difficulties to be overcome before the steam turbine can be considered thoroughly satisfactory, the progress in its development has been and continues to be remarkably rapid.

Steam Consumption.—Nevertheless there have not yet, except possibly at uncommercially low exhaust pressures, been obtained with steam turbines such good results, as regards low steam consumption, as have frequently been obtained with the best modern piston engines of certain types. Thus a careful analysis of a large number of results has shown that the curves of Fig. 25 may fairly be taken as representing the steam consumption of piston engines and steam turbines respectively, when operated under reference conditions which may be considered as normal and commercial. These reference conditions are:—

Admission pressure = 13 kg per sq cm (absolute).
Superheat = 50° (actual temperature of steam = 241°).
Exhaust pressure = 0,15 kg per sq cm (absolute).

Representing by 100 the full load steam consumption under the above reference conditions, then the variation in the full load steam consumption with varying admission pressure, superheat and exhaust pressure, may be taken as shown in Fig. 26. Of course these rates of variation differ greatly with the type and size of piston engine and of turbine. Also, the rate of variation—say with varying exhaust pressure—varies with differences in the accompanying superheat and admission pressure. But the extent of these variations has as yet been insufficiently investigated, and we cannot at present do better than abide by the curves of Fig. 26.

Corresponding to Fig. 26 for full load, we have Fig. 27 for ½ load, and Fig. 28 for ¼ load. By means of the curves in Figs. 25 to 28

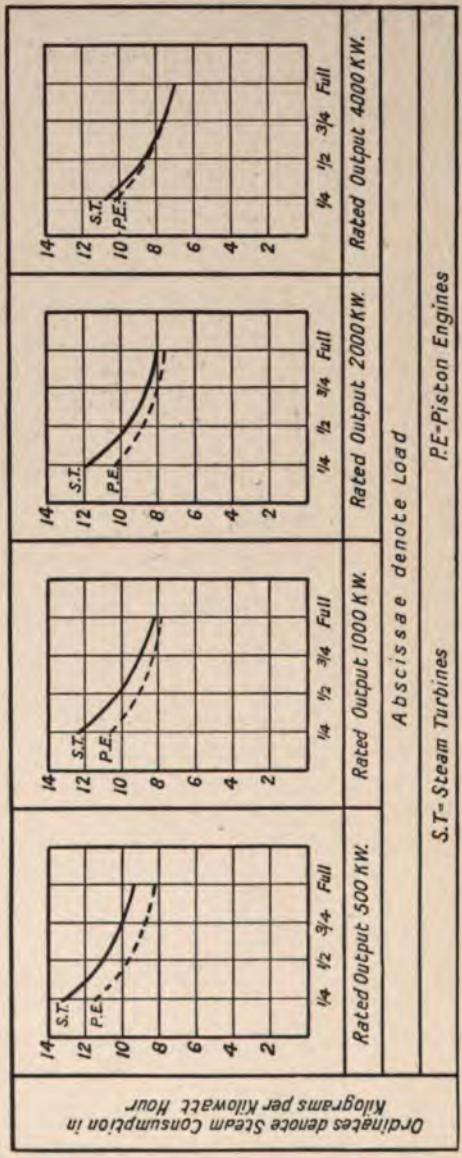


Fig. 25. Representative Data of Steam Consumption of Steam Turbines and Piston Engines.

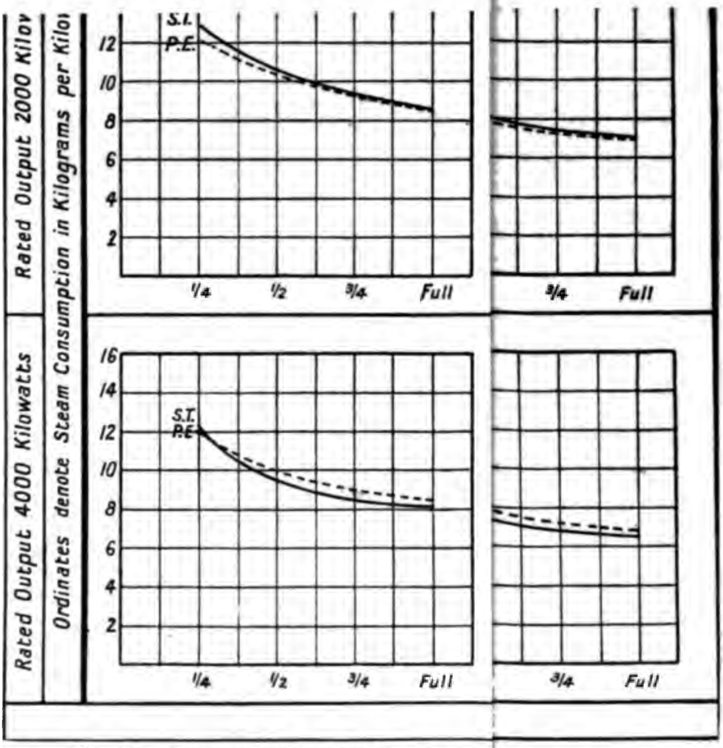


Fig. 29. Curves of Steam Consumpti[illegible]ious Conditions

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the curves in Fig. 29 are readily deduced. These give as fair a representation of the present relative steam consumption of the two types of engine as can be arrived at by analysis of the results at present available.

The curves of Figs. 26 to 28 show the effects of different admission pressures, degrees of superheat, and exhaust pressure. The exhaust pressure plays a very important part in the economy of steam turbines. A given amount of superheat effects slightly greater improvement in the economy of a piston engine than in that of a steam turbine, but in both cases the improvement by employing high degrees of superheat is very considerable. While the admission pressure makes comparatively little difference as regards the economical working of turbines, high admission pressures are very necessary with piston engines. This is a distinct advantage in favour of turbines, since by using lower admission pressures, higher degrees of superheat may be used without encountering prohibitive temperatures. As already stated, the effect of superheat in decreasing the steam consumption of turbines is considerable. This is in great part due to the decrease in condensation within the turbine and the consequently decreased friction.

The greatest improvement in economy of steam turbines is effected by the employment of low exhaust pressures, as the curves of Figs. 26, 27 and 28 show. The mechanical losses (*i.e.*, the losses due to bearing friction and to the friction of the steam against the blades) are very much reduced when a low exhaust pressure is employed.

With the object of giving an illustration of the allocation of the component losses in a steam turbine, and of finding the direct effects of various superheats and exhaust pressures, an investigation of a hypothetical 1000 kw turbo generator has been carried out, and from this investigation Table LI. has been prepared.

The investigation has been made for the 1000 kw turbo generator when running with an absolute steam pressure of 13 kg per sq cm at admission. The steam consumptions of this set at full load and under various degrees of superheat and exhaust pressure have been obtained from the curves of Fig. 26.

When running with saturated steam and non-condensing, and at an admission pressure of 13 kg per sq cm, a well-designed turbine of 1000 kw rated capacity may have a steam consumption of 13,1 kg per kw hr at rated load. In order to analyse the losses in the turbine, it is necessary to know the effect of various

exhaust pressures and superheat on the friction, as the losses due to the friction vary greatly with the amount of moisture in the steam. It is to be regretted that thoroughly comprehensive test results for modern turbines of large capacity are not available. Thus, in order to arrive at some idea of the effect of the exhaust pressure and superheat on the various losses, it has been necessary to make preliminary assumptions for the thermodynamic efficiency of the turbine when operating under various conditions. If the thermodynamic efficiency of the turbine be multiplied by the efficiency of the generator, the result gives the combined thermodynamic efficiency of the turbine and generator.

The efficiency of a 1000 kw dynamo may be taken at 95 per cent. The thermodynamic efficiencies assumed and set forth in column *g* of Table LI. are based on general conclusions deduced from numerous tests that have been carried out on turbines of various sizes and types, and operated under various conditions. These efficiencies may be taken as values which, although at present only rarely approached, are, with the rapid developments now occurring, to be considered as fair. From these values, and the steam consumption curves in Fig. 26, we have sufficient data to determine the wetness of the steam as it leaves the cylinder.

The calculation is shown in Table LI. for steam at a pressure of 13 kg per sq cm superheated 0°, 50° and 100°, and expanded to pressures of 1,00, 0,50, and 0,15 kg per sq cm.

In Table LI. column *c* gives the rate of steam consumption, obtained from Figs. 25 and 26. From this column is then obtained the total steam consumption in tons per hour at rated load of 1000 kw. This is inserted in column *d*. Column *e* gives the heat required to raise one ton of steam to the given temperature at a pressure of 13 kg per sq cm from water at 0° C. In column *f* is entered the total heat thus supplied to the turbine per hour. In column *g* is entered the combined efficiency of the turbine and generator obtained as explained above. Column *h* gives the losses corresponding to this efficiency, when the set is running at its rated load.

The amount of heat supplied to the turbine per hour consists of three components:—

(1) The heat dissipated in the turbine and dynamo by friction and radiation.

(2) The heat transformed into useful electrical energy.

(3) The heat of the mixture of steam and water discharged from the turbine.

TABLE LI.

The Wetness Factor of the Exhaust Steam from a 1000 Kw Turbo Generator Working at Full Rated Load under various Conditions.

Superheat in Deg. Cent.	Exhaust Pressure in Kg per Sq Cm (absolute).	Steam Consumption.		Steam Heat at Admission.		Combined Efficiency of Turbine and Dynamo.	Heat Dissipated per Hour $= \left(\frac{1000 \times 100}{g} - 1000\right)$	Heat of Discharge.		Steam Heat of Saturated Steam at Exhaust Pressure from Table III.	Heat of Condensation = m − l.	Latent Heat at Exhaust Pressure from Table III.	Wetness Factor = n ÷ o.
		Kg per kw hr from Fig. 26.	Tons of steam per Hour $= \frac{c \times 1000}{1000}$	kw hr per Ton from Table III.	Total per Hour = d × e.			Total per Hour = f − (h + 1000)	kw hr per Ton = k ÷ d				
a	*b*	*c*	*d*	*e*	*f*	*g*	*h*	*k*	*l*	*m*	*n*	*o*	*p*
0	1,00	13,1	13,1	777	10 200	56 %	780	8420	644	741	97	626	0,155
	0,50	11,2	11,2	"	8700	59 %	700	7000	625	733	108	639	0,169
	0,15	9,0	9,0	"	7000	66 %	510	5490	610	720	110	657	0,167
50	1,00	11,8	11.8	810	9550	58 %	720	7830	664	741	77	626	0,123
	0,50	10,1	10,1	"	8180	63 %	590	6590	652	733	81	639	0,127
	0,15	8,1	8,1	"	6570	68 %	470	5100	630	720	90	657	0,137
100	1,00	10,9	10,9	842	9190	60 %	670	7520	690	741	51	626	0,082
	0,50	9,4	9,4	"	7900	65 %	540	6360	677	733	56	639	0,088
	0,15	7,5	7,6	"	6400	70 %	430	4970	655	720	65	657	0,099

The total heat supplied is tabulated in column f, the first component in column h, and the rate of expenditure of useful electrical energy at rated load is equal to 1000 kw, that is 1000 kw hr per hour. Thus the third component can be obtained by simple subtraction, and is inserted in column k.

Dividing by the weight of steam used per hour (column d), we obtain the heat of one ton of the mixture discharged from the

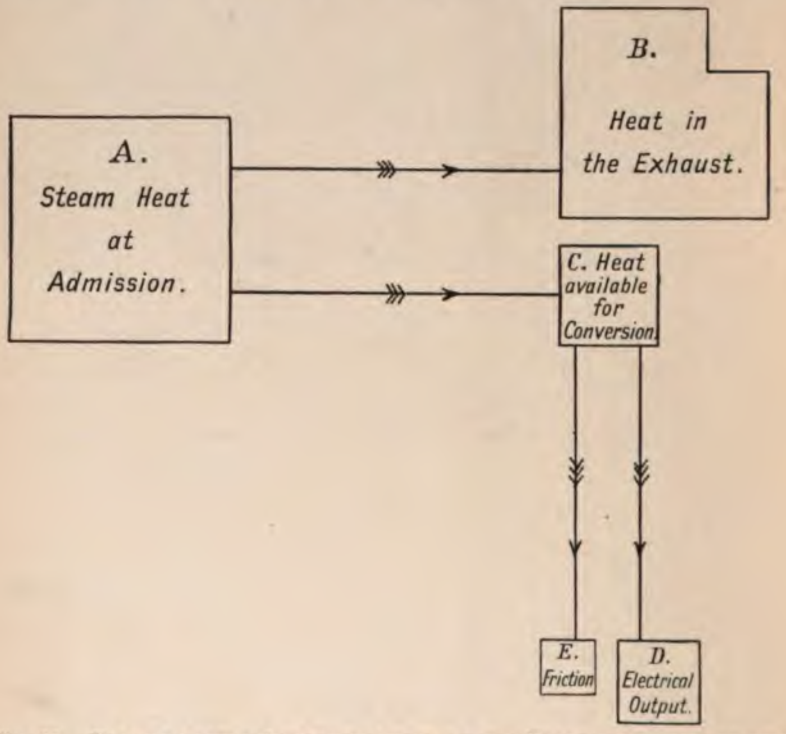


Fig. 30. DIAGRAMMATIC REPRESENTATION OF THE TRANSFORMATION OF THE HEAT OF STEAM INTO ELECTRICAL ENERGY.

turbine. If now we note the steam heat of saturated steam at the exhaust pressure (column n), the difference will give the amount of heat corresponding to the water condensed in the cylinder. This amount of heat, divided by the latent heat of steam at the exhaust pressure, gives the wetness factor of the exhaust mixture.

Table LI. may now be represented diagrammatically as in Fig. 30. In this figure the square A is set off to scale to represent the steam heat in kw hr per ton of steam admitted to the cylinder, as recorded

in column *e* of the Table. To the same scale is set off the area B to represent the heat per ton of mixture discharged from the cylinder (column *l*). The difference between the areas A and B represents the energy set free by the expansion of the steam in the cylinder. This is shown in the diagram by the square C. This amount of energy is still further transformed into useful electrical work, and into wasted heat, as indicated by the squares D and E.

The areas in Fig. 30 are scaled off to represent the case of a

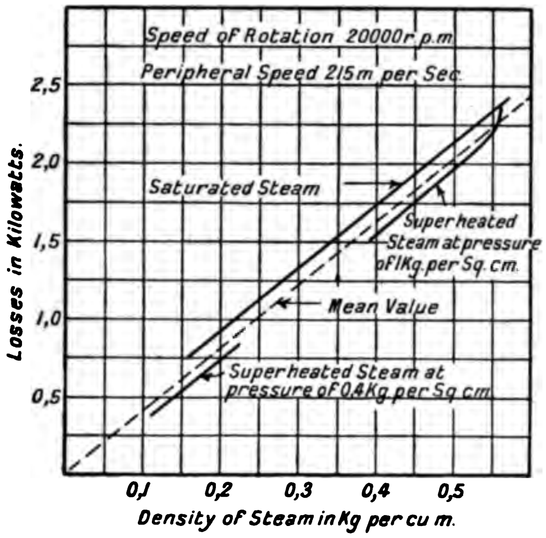


Fig. 31. Showing how the Friction Losses due to the Rotation of a 22 kw de Laval Turbine Wheel vary with the Density of the Surrounding Steam.

(Note.—The Friction of the Bearings has been deducted.)

1000 kw turbo generator working at rated load with steam at an admission pressure of 13 kg per sq cm, superheated 50° C, and expanded to an absolute pressure of 0,15 kg per sq cm. The steam heat at admission is 810 kw hr per ton. The heat of discharge is 630 kw hr per ton, so that 180 kw hr per ton of steam are available for conversion into work. But for the rated output of 1000 kw, 8,1 tons of steam are required per hour, so that one ton of steam only provides $\frac{1000}{8,1} = 124$ kw hr of useful electrical energy.

Hence the friction losses per ton of steam amount to $180 - 124 = 56$ kw hr.

It will be noticed that the area B in Fig. 30 is not, like the others, a complete square. It has been drawn as shown for the purpose of indicating the amount of heat set free by the condensation of steam in the cylinder. If the area B is completed to form a perfect square, it represents the steam heat of saturated steam at the exhaust pressure.

The results arrived at in Table LI. show the great influence

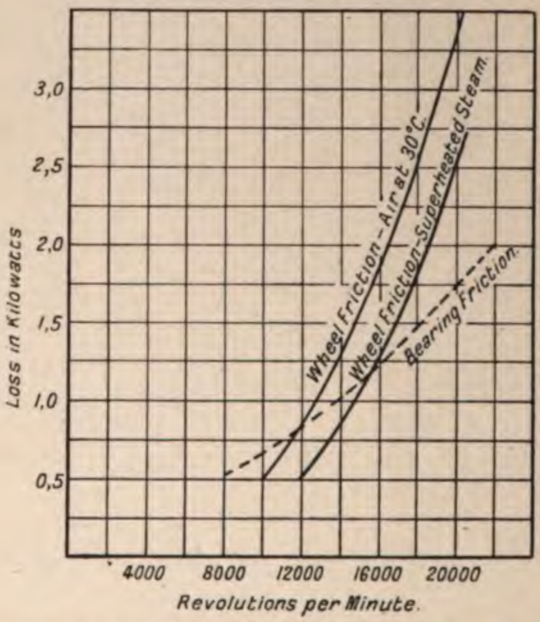


Fig. 32. Showing how the Friction Losses in a 22 kw de Laval Turbine vary with the Speed.

(Note.—The Pressure of the Air and the Steam is 1 kg per sq cm.)

exerted on the efficiency by the wetness factor and the exhaust pressure. In the interests of a low friction loss, and consequently of a high efficiency and low steam consumption, the blades of the steam turbine must run in as dry and rare a medium as practicable. Tests have been made by the late Prof. Lewicki which throw considerable light on the influence of the density, dryness and material of the medium, on the friction losses of wheels revolving in that medium.

The curves in Fig. 31 are plotted from the results of three series

of Lewicki's tests on a 22 kw de Laval turbine, running at 20 000 revolutions per minute, the corresponding peripheral speed being 215 m. per second. The bearing friction has been deducted and

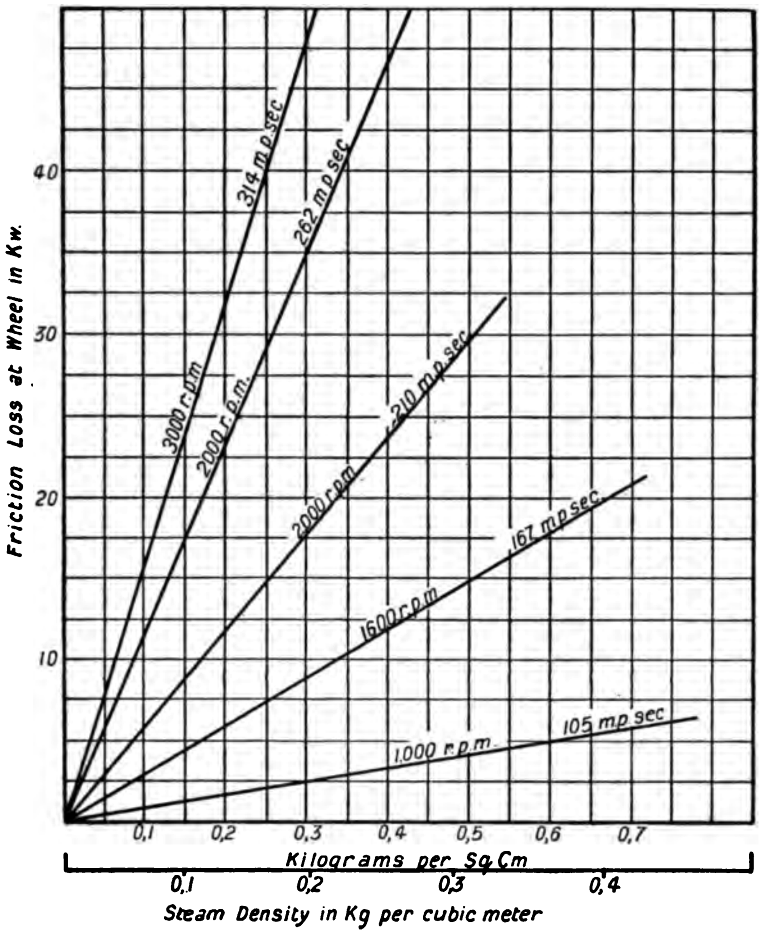


Fig. 33. Friction Loss of Wheel Revolving in Steam of Various Densities.—From R. Rötscher.

the mean result is given by the dotted line, which shows that the loss is directly proportional to the density of the steam.

The peripheral speed has a preponderating influence on the friction of the wheel. The curves in Fig. 32 show the losses in this 22 kw turbine when run at varying speeds. The full line curves

represent the losses due to the rotation of the wheel (after deducting the bearing losses), when running in air at a temperature of 30° C and in saturated steam respectively, the pressure in both cases being 1 kg per sq cm.

The dotted curve in the same figure represents the friction losses at the bearings. It is seen that the wheel friction increases with the speed at a much more rapid rate than the bearing friction.

Tests of the wheel friction have also been made by Rötscher,[1] certain of the results of which are plotted in the curves of Fig. 33. In these curves the exhaust pressures in kg per sq cm, and also the densities in kilograms per cubic meter, are employed as abscissae, and the friction losses of the wheel (exclusive of bearing friction) are

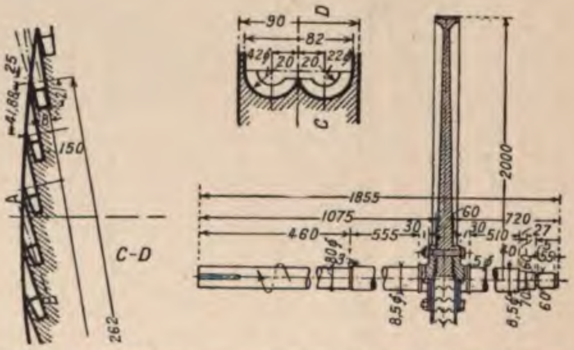


Fig. 34. Riedler-Stumpf 2000 Horse Power Wheel.

employed as ordinates. Against each curve are written the speed in revolutions per minute and the peripheral speed in meters per second. These tests were made on a 2000 hp Riedler-Stumpf steam turbine, which employs a single wheel of 2 meters diameter. This wheel is shown with dimensions in Fig. 34.

From an analysis of these results, it appears that the wheel friction (exclusive of bearing friction) is proportional to the 2,8th power of the speed and is proportional to the first power of the density of the medium in which it revolves. The results are in good agreement with Stodola's earlier estimate that the wheel friction is proportional to the 2,9th power of the speed.

Fig. 35 gives the results of tests[2] made by Professor Belluzzo of

[1] "Zeit. des Vereines deutscher Ingenieure," April 27, 1907, p. 658.
[2] "Versuche über die Reibung roturinde Turbinenscheiben," von G. Belluzzo. Zeitschr. ges. Turbinenwesen, p. 219—221, May 18, 1907.

Milan, which show the wheel friction losses (exclusive of bearing friction) as a function of the steam pressure and corresponding densities of steam at 10° superheat. The two curves shown correspond to the two wheels in Fig. 36, the wheel with the larger blades naturally causing a greater loss.

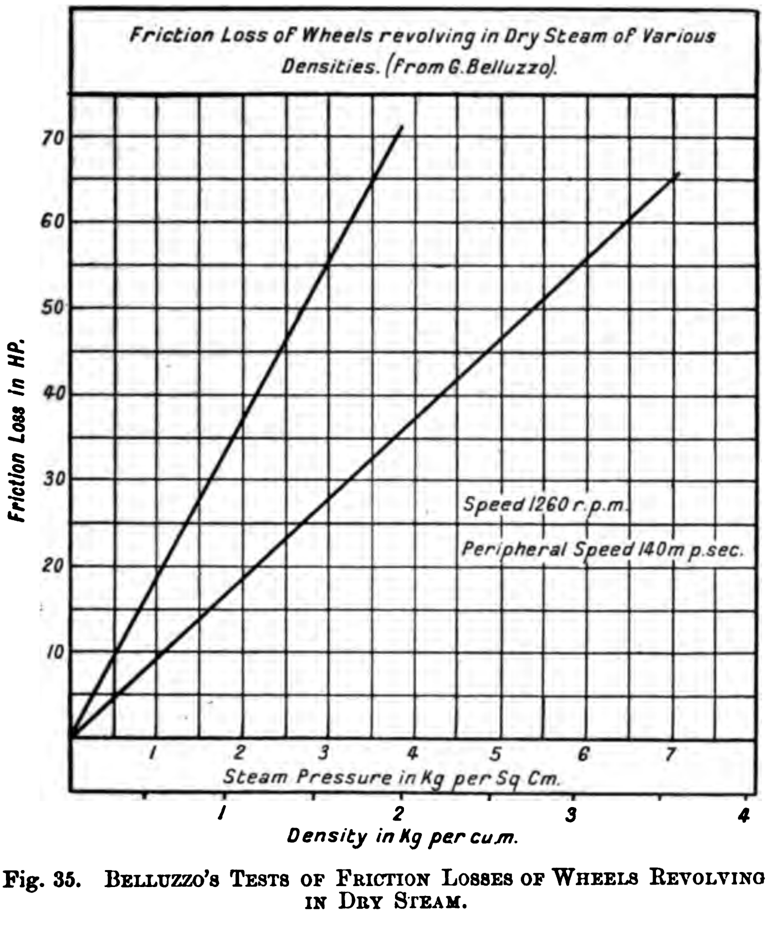


Fig. 35. BELLUZZO'S TESTS OF FRICTION LOSSES OF WHEELS REVOLVING IN DRY STEAM.

Hence, so far as relates to obtaining low friction losses, the peripheral speed of the rotors of steam turbines should be low. But this is diametrically opposed to the conditions which should obtain in order that a maximum percentage of the kinetic energy of the steam may be transferred to the rotor in the form of mechanical

energy. Thus, suppose a perfectly elastic body,[1] with a mass M, of 1 kg, to be travelling in a straight line through a frictionless medium (in a region where the acceleration due to gravity is equal to 9,8 metres per second per second) at a uniform velocity, V, of

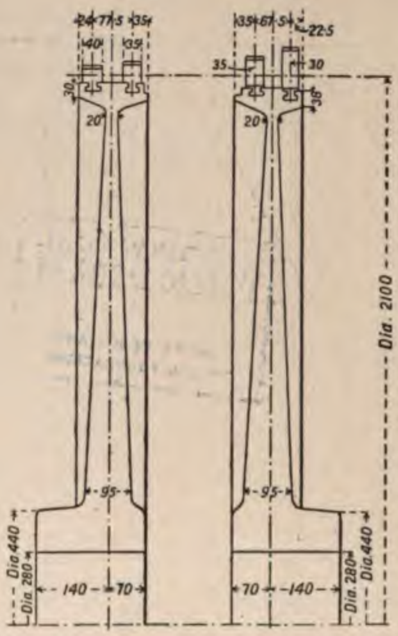


Fig. 36. TURBINE WHEELS AND BLADES WITH WHICH THE CURVES OF FIG. 35 WERE OBTAINED.

1000 metres per second. The kinetic energy of this body, *i.e.*, the energy possessed by it in virtue of its motion, is equal to $\frac{1}{2}\ M\ V^2$, or

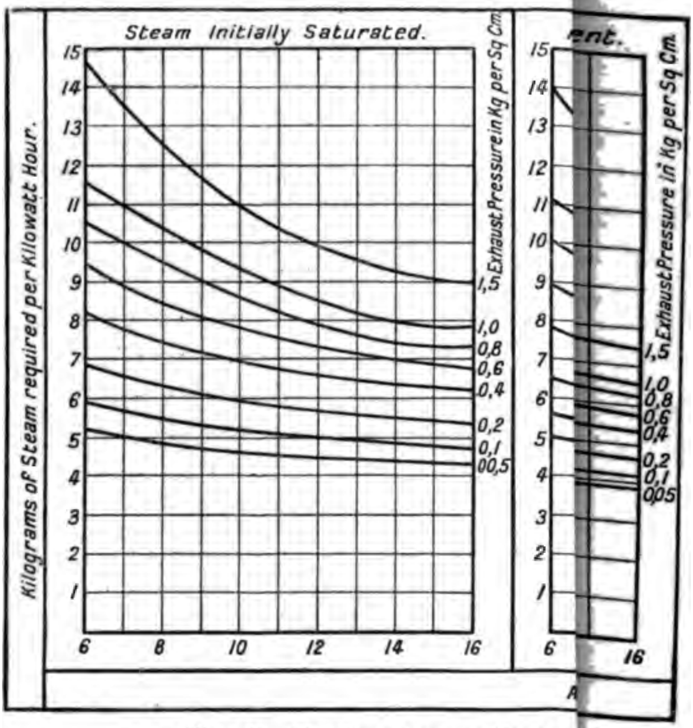
$$\tfrac{1}{2} \times \frac{1}{9{,}8} \times 1000^2 = 51\,000 \text{ kilogrammeters.}$$

Suppose this body to collide with a far larger perfectly rigid body moving in the same direction at one-half the speed, *i.e.* at a speed of 500 meters per second, the relative speed of the two bodies before contact being 1000 − 500 = 500 meters per second. Its motion relatively to the far larger body will, in virtue of the collision, be reversed in direction. That is to say, the perfectly elastic body of one kilogram will, relatively to the far larger body, precisely reverse

[1] It is convenient to mentally picture this body as a sphere.

PLATE V.

Fig. 41.



Figs. 41—44. SHOWING THE STEAM

85.

its direction and will assume a relative velocity of 500 meters per second away from this far larger body. But since the larger body continues to move forward at substantially the same speed which it possessed before the collision, *i.e.*, at a speed of 500 meters per second, the absolute speed of the first body has become $500 - 500 = 0$ metres per second, *i.e.*, it remains motionless in space, and hence has given up its entire kinetic energy to the far larger body.

Substituting the bladed rim of the revolving wheel of the steam turbine for the "far larger body," and one kilogram of steam for the "perfectly elastic body," we at once see that the speed of the blades should preferably approach one-half the speed of the impinging steam. For were this the case, and were both bodies, *i.e.*, the blades and the steam, perfectly elastic, and were the steam to impinge from a direction normal to the plane of the blades at the point of impact, then the steam would be left stationary in space by the moving blades and depleted of its kinetic energy. Since the direction of impact is *not* normal, and since the bodies concerned are *not* perfectly elastic, this ideal velocity is only a rough guide; and furthermore, the present state of engineering knowledge is so limited that out of consideration for the constructional standpoint, much lower peripheral speeds are generally employed than correspond to half the speed of the impinging steam. The great decrease in the friction loss accompanying a moderate decrease in the peripheral speed constitutes additional justification for wide departures from this theoretical speed.

From the curves in Figs. 4 to 7 of Chapter I. have been deduced the curves of Figs. 37 to 40 showing the speed of the steam when emerging from a correctly proportioned and frictionless diverging nozzle supplied at various pressures and temperatures. It is seen that the speed is of the order of 1000 meters per second.

The method of deriving the curves of Figs. 37 to 40 will be understood from the following example:—

From Fig. 5 we find that when steam at an admission pressure of 10 kgs per sq cm and at a temperature of 200° C (*i.e.*, with 21° C of superheat) is used down to an exhaust pressure of 0,10 kg per sq cm, the energy rendered available for conversion to mechanical work amounts to 197 kw hrs per ton.

$$1 \text{ kw hr} = 367 \text{ ton meters.}$$

Hence we have available for conversion

$$197 \times 367 = 72\,000 \text{ ton meters}$$

per ton of steam consumed, or 72 000 kg m per kg of steam consumed.

$$\therefore \tfrac{1}{2} \times \frac{1}{9{,}8} \times V^2 = 72\,000$$

$$V = \sqrt{1\,410\,000}$$

$$= 1190 \text{ meters per second.}$$

This is the value plotted against the next to the upper curve of Fig. 38. The other values have been obtained in an equivalent manner.

Owing to losses due to the friction of the steam against the sides of the admission nozzle, slightly less values are actually obtained.

We may readily so rearrange the data in Figs. 4 to 7 as to give us the consumption of an engine with 100 per cent. thermodynamic efficiency. Thus for a steam turbine in which the steam is worked between an admission pressure of 10 kg per sq cm and an exhaust pressure of 0,10 kg per sq cm, the energy available for conversion into mechanical work is 197 kw hr per ton or

0,197 kw hr per kg.

Consequently, if the steam turbine had a thermodynamic efficiency of 100 per cent., its consumption would be

$$\frac{1{,}00}{0{,}197} = 5{,}1 \text{ kg per kw hr.}$$

This is the value plotted for the appropriate curve of Fig. 42, and the remaining values for this and the other curves in Figs. 41 to 44 are plotted in a similar manner.

In Fig. 45 are plotted for an admission pressure of 13 kg per sq cm an exhaust pressure of 0,15 kg per sq. cm and 50° C of superheat at admission, representative curves for the steam consumption of modern piston engines and steam turbines, and also a reference line corresponding to 100 per cent. thermodynamic efficiency. Corresponding curves for half load are given in Fig. 46. The deduction of the curves in Figs. 47 and 48, from the data in Figs. 45 and 46, is obvious.

Allusion has already been made to the comparative futility of employing high boiler pressures for steam turbine plant. In some recently published investigations of Rötscher[1] tests are described which bring this out very forcibly. From a large number of steam consumption tests at various speeds and steam pressures, data were

[1] "Zeit. des Vereines deutscher Ingenieure," April 20, 1907, p. 605.

PLATE VII.

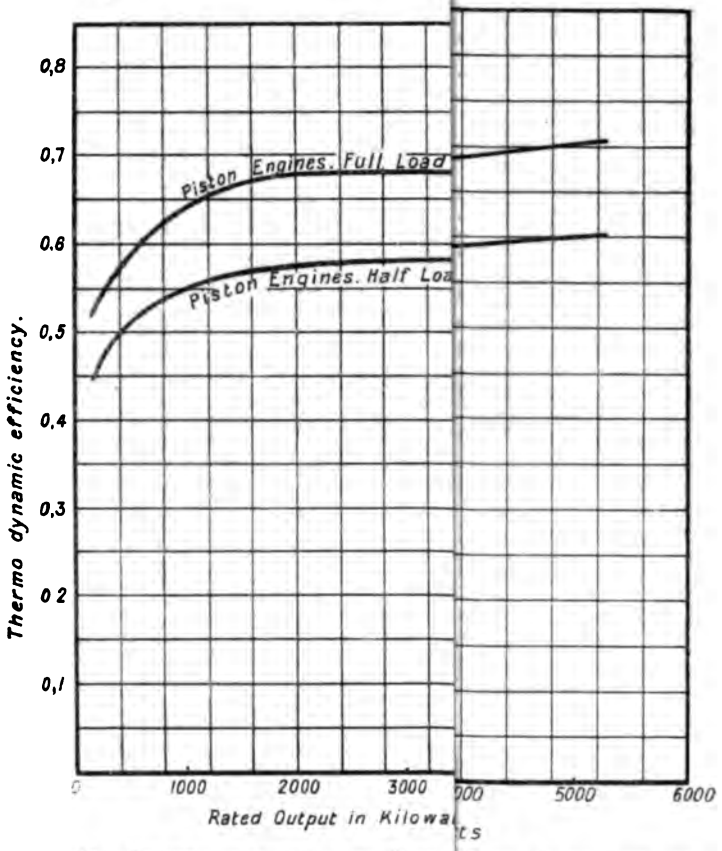


Fig. 47. CURVES SHOWING THE THERMNAMIC EFFICIENCY OF REPRESENTATIVE PISTON ENGINES ATED LOAD AND HALF RATED LOAD.

[To face p. 87.

obtained from which the curves in Fig. 49 have been plotted. Unfortunately, from Rötscher's data as published, the precise steam temperatures at admission, and the precise exhaust pressures corresponding to these curves, cannot be allocated with certainty, but the general order of these quantities during the tests appears to have been as stated on the curves. Rötscher states that his investigations will be described in complete detail in a forthcoming issue of the "Mitteilungen über Forschungsarbeiten."

The conditions under which Rötscher carried out his investigations were not such that he could obtain the steam consumptions at

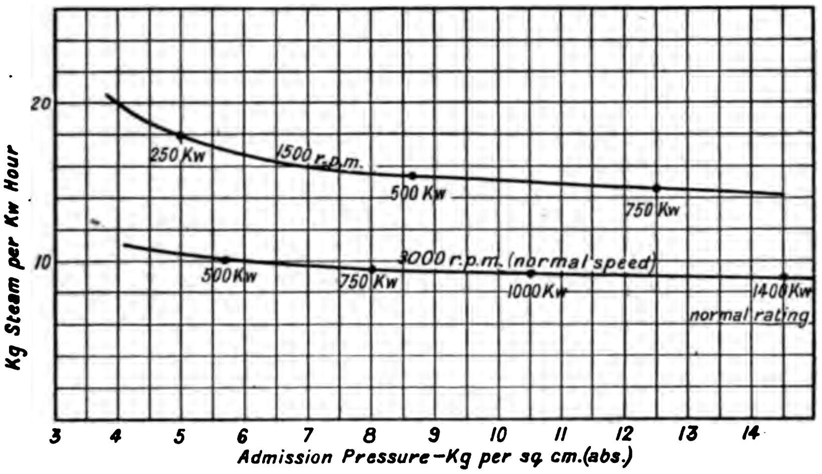


Fig. 49. Steam Consumption as Function of Admission Pressure. The Admission Pressure = 200 to 250° C. Exhaust Pressure = 0,05 to 0,15 kg per sq cm.

a given speed and various admission pressures for any one particular load throughout the range. Thus, as will be seen from the curves in Fig. 49, the loads ranged from some 10 per cent. to 30 per cent. of rated load at the lower pressures, well up to full load at the higher pressures. This, however, in nowise invalidates the important conclusion which the present author desires to draw from these tests, namely, that the decrease in steam consumption obtainable by the employment of high admission pressures is in the case of steam turbines (at any rate of the type and design in question) exceedingly slight. Thus, since the steam consumption at light loads is always greater than at rated load, it follows that had the rated load

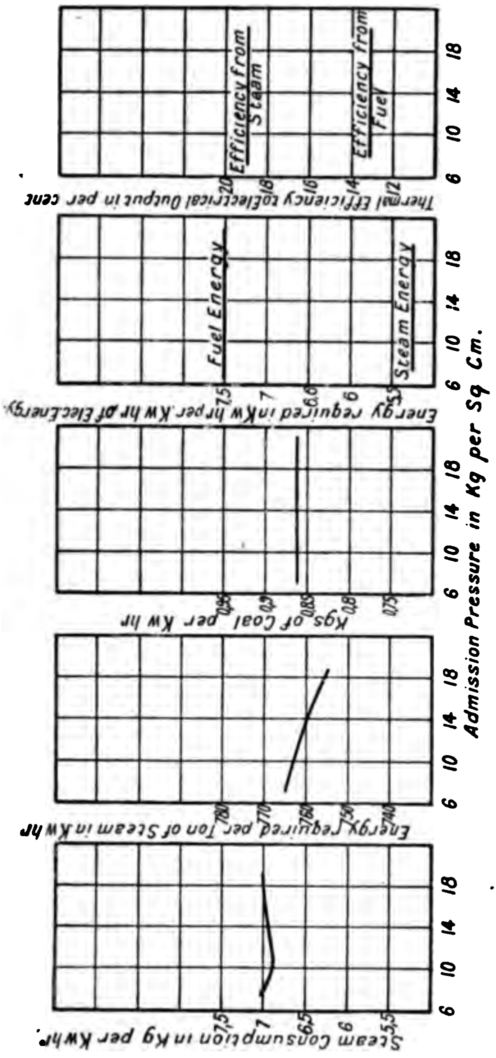
been maintained down to the lower pressures, the curves of Fig. 49 would have much more nearly approached horizontal lines; in other words, the steam consumption would have been much more nearly independent of the admission pressure. Thus, were the steam consumption absolutely independent of the admission pressure, then the lower curve shows that at 3000 rpm the steam consumption at quarter load is only some 20 per cent. greater than at rated load. Now the steam consumption at quarter load is, as is well known, rarely so low as only 20 per cent. in excess of the steam consumption at rated load, and we may safely say that it is certainly no lower than 15 per cent. greater than the steam consumption at rated load. Taking this latter figure, the increased economy at 13 atmospheres as compared with that at 4 atmospheres is only a matter of some 5 per cent. At the speed of 1500 rpm these statements do not apply to as great an extent, but this turbine was designed for a rated speed of 3000 rpm and the conditions at 1500 rpm are abnormal, this speed having simply been employed for experimental purposes.

Since, however, we have before us these tests for the two speeds, it would appear interesting to examine the effect of thus decreasing the speed to one-half. Let us, with this purpose in view, compare the steam consumptions at outputs of 500 and 750 kw respectively. For both of these loads the steam consumption at the lower speed works out at some 50 to 55 per cent. greater than at rated speed of 3000 rpm. This bears out the arguments already set forth to the effect that the steam turbine on the whole benefits considerably by design and operation at high rated speeds, but the case is not so serious for low speeds as these figures would indicate, for this particular turbine was designed for 3000 rpm. Turbines for the same rated output when designed expressly for the lower speed, namely, 1500 rpm, have much lower steam consumptions at this low speed than this turbine, which was only run at the low speed for experimental purposes and naturally was, under these conditions, distinctly handicapped.

Figs. 50 to 55 relate to an investigation of the effect, at normal rated load, of varying admission pressures when constant steam temperature at admission and constant exhaust pressure of 0,15 kg per sq cm are maintained. The calculations have been made for a 4000 kw turbo generator of the Parsons type. The first five curves relate to a steam temperature of 250° C at admission. Let us follow through the calculations for an admission pressure of 18 kg per sq cm.

From Fig. 25 it is seen that, at rated load, an admission pressure of 13 kg, 50° C of superheat, and an exhaust pressure of 0,5 kg, the

Fig. 50. Fig. 51. Fig. 52. Fig. 53. Fig. 54.



Figs. 50—54. Variation of Steam Consumption and Efficiency with Admission Pressure, calculated for a 4000 kw Parsons Type Steam Turbine, at Constant Steam Temperature of 250° C.

Exhaust Pressure = 0,15 kg per sq cm. Feed Water Temperature = 50°. Boiler Efficiency = 70 per cent. Calorific Value of Coal, 8700 kw hr per ton.

steam consumption of a 4000 kw set is 7 kg per kw hr. From Fig. 26 we find that the steam consumption at an admission pressure of 18 kg per sq cm is 0,985 as great, *i.e.*,

$$7 \times 0{,}985 = 0{,}69 \text{ kg per kw hr.}$$

The saturation temperature for a pressure of 18 kg is 206° C. Therefore, to raise the steam to a temperature of 250° C, the superheat will be 44° C. From Fig. 26 we find that the steam consumption at 44° C superheat is 1,01 as great as that at 50° C superheat. Therefore the steam consumption at 18 kg admission pressure and 44° C superheat will be

$$0{,}69 \times 1{,}01 = 0{,}70 \text{ kg}.$$

In like manner the steam consumption for various admission pressures has been estimated and the results are expressed in the curve of Fig. 50. For the same admission pressure of 18 kg let us proceed to estimate the amount of energy required per ton of steam. The feed-water is supplied at a temperature of 50° C. To raise one ton of water from 50° C to 206° C, the temperature of saturated steam at 18 kg pressure, we require 189 kw hr. This figure may be derived from Table I. on p. 4 of Chapter I.

The total latent heat of evaporation at this pressure is 536 kw hr per ton (see Table III.), and to raise the temperature further from 206° to 250° C we require another 31 kw hr per ton, making a total of 756 kw hr per ton of steam. Calculations have been made for other admission pressures, and the results are given in the curve of Fig. 51.

The boiler plant is assumed to have an efficiency of 70 per cent.; therefore for every 756 kw hr given up to the steam we must supply fuel with a calorific capacity of

$$\frac{756}{0{,}7} = 108 \text{ kw hr}.$$

From Fig. 50 the steam consumption per kw hr is 7 kg; therefore for these 1080 kw hr of fuel supplied to the boiler

$$\frac{1000}{7} = 143$$

kw hr are delivered by the dynamo.

Therefore the kw hr of fuel supplied to the boiler per kw hr of electrical energy is

$$\frac{1080}{143} = 7{,}55 \text{ kw hr}.$$

The fuel employed has a calorific capacity of 8,7 kw hr per kg. Therefore the amount of fuel consumed per kw hr is

$$\frac{7{,}55}{8{,}7} = 0{,}865 \text{ kg}.$$

This fuel consumption has also been calculated for various admission pressures and the results have been plotted in Fig. 52.

The energy required per kw hr of electrical energy is shown in

Fig. 53. As shown above, the fuel energy is 7,55 kw hr in this particular case, and as the boiler efficiency is 70 per cent., the steam energy is

$$0,7 \times 7,55 = 5,3 \text{ kw hr.}$$

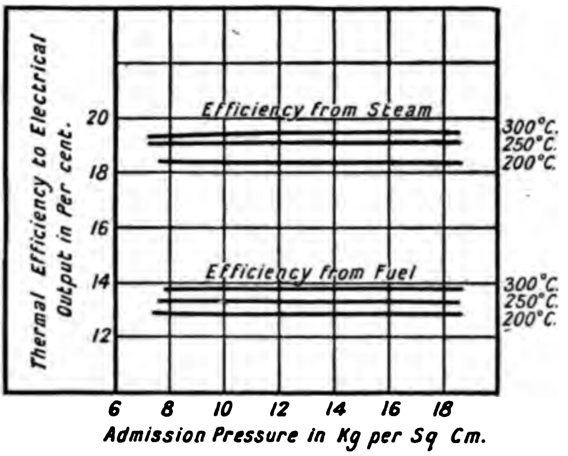


Fig. 55. SHOWING THE THERMAL EFFICIENCIES FOR VARIOUS STEAM TEMPERATURES AS A FUNCTION OF THE ADMISSION PRESSURE.

Feed Water Temperature = 50° C. Exhaust Pressure = 0,15 kg per sq cm. Boiler efficiency = 70 per cent. Calorific Value of Fuel = 8700 kw hr per ton.

In Fig. 54 are shown the efficiencies. The thermal efficiency from steam at 18 kg admission pressure is

$$\frac{1}{5,3} = 19 \text{ per cent.,}$$

and the thermal efficiency from fuel is

$$\frac{1}{7,55} = 13,2 \text{ per cent.}$$

Fig. 55 shows these thermal efficiencies, and also the thermal efficiences for steam temperatures of 200° and 300° C.

CHAPTER V

CONDENSING PLANT

We have seen that for steam turbine installations, low steam consumption is only obtainable by means of a low exhaust pressure. While with piston engine plant an exhaust pressure of 0,20 kg per sq cm gives fair results, such low pressures as 0,15 to 0,10 kg per sq cm are absolutely necessary to obtain reasonably low steam consumptions with steam turbines, and installations are sometimes estimated on the basis of an exhaust pressure of 0,05 kg per sq cm.

In order to obtain these low pressures circulating water of low temperature must be available, and in large quantities. The quantity required is so large that if any appreciable charge per 1000 gallons is made, it is usually cheaper to install cooling towers and employ the circulating water over and over again.

By the time the necessary outlay for condensing plant of sufficiently large capacity and for cooling towers has been estimated, the advantages of steam turbines as regards savings effected through decreased floor space and in other directions will often be found to have been more than outweighed. Thus the subject of condenser calculations has now become one of much importance. We have seen that when heat is absorbed by water the temperature rises, and at some definite temperature, called the temperature of vaporisation, the water commences to evaporate. This temperature of vaporisation is a function of the absolute pressure, and has been given in Table III. on p. 8. It is again given for low pressures in the second column of Table LII. When all the water has been evaporated, any further addition of heat causes a renewed rise in temperature, as has been shown by the curves in Fig. 2 on p. 6.

If we consider the reverse case, where heat is extracted from the steam, we find that the temperature of the steam falls until it reaches the temperature of vaporisation corresponding to the steam pressure. From this point any further abstraction of heat is accompanied by a condensation of the steam. The temperature remains constant until all the steam is condensed. Thus the temperature of vaporisation may equally correctly be termed the

"temperature of condensation." If still further heat is extracted from the water, the temperature once more begins to fall.

The heat that is required to change water into steam at the temperature of vaporisation is called the latent heat, and in the reverse process, this amount of heat must be extracted from the steam before it can bé completely condensed into water.

Let us now consider how we are to extract the necessary amount of heat from the steam. If a body at a lower temperature than the

TABLE LII.

The Heat absorbed by one Ton of Circulating Water.

Exhaust Pressure in Kg per Sq Cm.	Temperature of Vaporisation in Deg. Cent.	Kw hr absorbed by one Ton of Circulating Water when Heated from the following Temperatures to the Temperature of Vaporisation of the Steam.												
		0° C.	5° C.	10° C	15° C.	20° C.	25° C.	30° C.	35° C.	40° C.	45° C.	50° C.	55° C.	60° C.
0,02	17	20	14	8	2									
0,04	29	34	28	22	16	10	5							
0,06	36	42	36	30	24	19	13	7	1					
0,08	41	48	42	36	30	25	19	13	7	1				
0,10	46	53	48	42	36	30	24	19	13	7	1			
0,12	49	57	51	45	39	34	28	22	16	10	5			
0,15	54	63	57	51	45	40	34	28	22	16	10	5		
0,20	60	70	64	58	52	46	41	35	29	23	17	12	6	
0,25	65	75	70	64	58	52	46	41	35	29	23	17	12	6
0,30	69	80	74	68	63	57	51	45	39	34	28	22	16	10
0,35	72	84	78	72	66	60	55	49	43	37	31	26	20	14
0,40	76	88	82	76	71	65	59	53	48	42	36	30	24	19

steam, is brought into proximity with the steam, the difference in temperature of the two bodies causes a flow of heat to the body of lower temperature.

Water is at present considered the most suitable substance to use for the purpose of extracting heat from steam with a view to its condensation. The capacity of water for absorbing heat is set forth in Table LII. In this Table, water is taken at various initial temperatures, 0°, 5°, etc., up to 60°. Calculations are then made of the heat necessary to raise its temperature to the temperatures indicated in the second column, which are the temperatures of vaporisation corresponding to the pressures given in the first column. We see,

for instance, that to raise the temperature of one ton of water from 0° to 17°, 20 kw hr of energy are necessary. We further see that if the initial temperature of the water had been 5°, only 14 kw hr would have been required to heat it to 17°, that is to say, one ton of water only absorbs 14 kw hr, when its temperature is raised from 5° to 17°.

We can now estimate the amount of water required to condense one ton of saturated[1] steam. In the third column of Table LIII. are recorded the latent heats of steam for the pressures tabulated in Table LII. We see that when the absolute pressure is 0,02 kg per sq cm, the latent heat is 680 kw hr per ton, and that the temperature of vaporisation (or condensation) is 17°. Since one ton of water absorbs 20 kw hr when its temperature is raised from 0° to 17°, it follows that to condense one ton of steam we require $\frac{680}{20} = 34$ tons of water at 0°, *if the temperature of the water is raised to* 17°.

The remaining portion of Table LIII. can be readily calculated in the same manner, and the results are shown graphically in Fig. 56, where the weight of water required to condense one ton of saturated steam is plotted against the initial temperature of the circulating water. It must be clearly understood that Table LIII. and Fig. 56 are based on the assumptions that the steam is saturated steam (*i.e.*, that it is neither superheated nor wet), and that the temperature of the water is raised to the temperature of the steam (*i.e.*, to the temperature of vaporisation corresponding to the pressure).

Let us now deal with the modifications necessary to give Fig. 56 a more general application.

(1) Difference of Temperature between the Steam and the Final Temperature of the Circulating Water.—As an example, let us consider one ton of saturated steam at a pressure of 0,15 kg per sq cm, and circulating water entering the condenser at an initial temperature of 35°, and emerging at a temperature 5° less than that of the steam, *i.e.*, at a temperature of 49° instead of 54°, the temperature of vaporisation of steam at a pressure of 0,15 kg per sq cm.

The heat absorbed by one ton of water is directly proportional to the rise of temperature (if we neglect the slight variations in the specific heat of water, as these are of no importance to engineers).

[1] When the term "saturated" steam is employed, it is to be understood that the steam is neither *superheated* nor *wet*.

But in Table LIII. and Fig. 56 the temperature rise of the water is assumed to be equal to the difference between the temperature of the steam and the initial temperature of the water. We are, however, unable to avail ourselves of the whole of this difference in temperature. Hence we must make a corresponding allowance by assuming that the water is heated to the temperature of the steam *from an initial temperature which exceeds the actual temperature by an amount equal to the final difference of temperature between the water and the steam.*

TABLE LIII.

Tons of Circulating Water required to Condense one Ton of Saturated Steam when the Temperature of the Water is raised to the Temperature of the Steam.

Exhaust Pressure in Kg per Sq Cm	Temperature of Vaporisation in Deg. Cent.	Latent Heat in kw hr per Ton.	Tons of Circulating Water required to Condense one Ton of Steam when the Circulating Water has the following Initial Temperatures.												
			0° C.	5° C.	10° C.	15° C	20° C.	25° C.	30° C.	35° C.	40° C.	45° C.	50° C.	55° C.	60° C.
0,02	17	680	34	52	85	300									
0,04	29	672	20	24	30	42	61	150							
0,06	36	667	16	19	22	28	35	51	95	580					
0,08	41	665	14	16	19	22	27	35	51	95	580				
0,10	46	663	12,5	14	16	18	22	28	35	51	95	570			
0,12	49	660	11,5	13	15	17	19	24	30	41	66	140			
0,15	54	657	10,5	12	13	15	17	19	23	30	41	60	140		
0,20	60	654	9,5	10	11	12	14	16	19	23	28	36	55	113	
0,25	65	650	8,7	9,3	10,0	11,0	12,5	14	16	19	22	28	38	54	113
0,30	69	647	8,1	8,8	9,5	10,0	11,5	13	14	16	19	23	29	40	66
0,35	72	645	7,7	8,3	9,0	9,5	10,5	12	13	15	17	20	25	32	46
0,40	76	642	6,6	7,8	8,5	8,0	10,0	11	12	13	15	18	21	28	36

Thus in our numerical example, the actual initial temperature of the water is 35°, but the final temperature of the water is 5°, less than the temperature of the steam, and in using Table LIII. and Fig. 56, we look for the weight of water corresponding to an initial temperature of 35° + 5° = 40°, and find that we require 41 tons of water per ton of steam.

We may now formulate the following rule for the use of Fig. 56. If the temperature of the water does not rise to the temperature of the steam, the amount of the difference should be added to the initial temperature of the steam. An ordinate in Fig. 56 through

the temperature thus obtained, will, at its intersection with the appropriate curve, give the weight of water required.

(2) Wet Steam.—If a mixture of steam and water is required to be transformed into water at the same temperature, the amount of

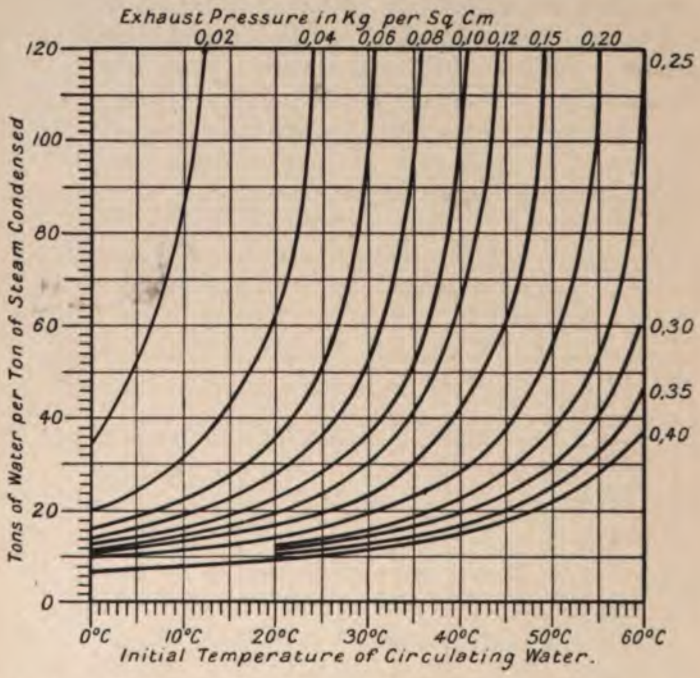


Fig. 56. Curves Showing the Quantity of Water required to Condense One Ton of Steam.

(Note.—The final difference of temperature between the water and the steam may be allowed for by adding it to the initial temperature on the above scale.)

circulating water required may be readily determined if the wetness factor is known.

Let us suppose that we have water at a temperature of 35° and that we require to condense one ton of steam at a pressure of 0,15 kg per sq cm and with a wetness factor of 0,10. That is to say, the mixture arriving at the condenser is composed of 0,10 ton of water, and 0,90 ton of steam.

The curves of Fig. 56 show that 30 tons of water are required to condense one ton of steam (provided the temperature of water rises

to the temperature of the steam), but we have seen that the mixture only contains 0,90 of a ton of steam, so that we shall only require $0,90 \times 30 = 27$ tons of water.

Thus the rule for wet steam is as follows: From the wetness factor, find the weight of water present in the mixture, and by subtraction obtain the net weight of steam requiring to be condensed. The curves of Fig. 56 may then be used in the ordinary manner.

(3) Superheated Steam.—If the steam is saturated, we have to extract from it only the latent heat in order to obtain complete condensation, but if the steam is superheated, we require to extract an additional amount of heat; as indicated in columns E, F and G of Table III on p. 8. The simplest method of performing the calculation is to find the weight of saturated steam (at the same pressure) which would involve the extraction of the same amount of heat.

Thus, if we require to condense one ton of steam at a pressure of 0,15 kg per sq cm and superheated 50°, we require to extract $657 + 28 = 685$ kw hr per ton. But saturated steam at this pressure would only require 657 kw hr per ton, so that one ton of this superheated steam is equivalent to $\frac{685}{657} = 1,04$ tons of saturated steam as regards the amount of heat requiring to be extracted to produce complete condensation.

If now the temperature of the circulating water is 35°, and if it can be raised to the temperature of vaporisation, we shall require 30 tons of water per ton of saturated steam, and $1,04 \times 30 = 31,2$ tons of water per ton of superheated steam.

General Problems.—Thus we see that all problems relating to the amount of water required to condense a given amount of steam can be solved from the elementary principle that

Heat gained by water = heat lost by steam.

As an example let us determine the weight of water required to condense 15 tons of steam under the following conditions: The water enters the condenser at a temperature of 23°, and is raised in the condenser to a temperature of 37°. The steam, which has a wetness factor of 0,17, enters the condenser at a pressure of 0,12 kg per sq cm, and the temperature of the hot well is 46°.

The steam heat of saturated steam at a pressure of 0,12 kg per sq cm is 717 kw hr per ton, and the heat of water at 46° is 53 kw hr per ton; so that every ton of saturated steam parts with

$717 - 53 = 664$ kw hr when it is condensed to water at 46°. The weight of the mixture is 15 tons, and the wetness factor is 0,17, so that the net weight of steam is $(1 - 0{,}17) \times 15 = 0{,}83 \times 15 = 12{,}5$ tons. Hence we require to extract $12{,}5 \times 664 = 8300$ kw hr from the steam. It only remains to find the weight of water required to absorb 8,300 kw hr, while the temperature of the water is raised from 23° to 37°.

The rise in temperature is $37 - 23 = 14°$. When one ton of water is heated through 1° it absorbs 1,16 kw hr. Hence when one ton is heated through 14°, it must absorb $14 \times 1{,}16 = 16{,}3$ kw hr, and the weight of water required is

$$\frac{8300}{16{,}3} = 510 \text{ tons.}$$

Types of Condenser.—Having obtained some idea of the function of a condenser, let us now briefly consider the principal types that have been adopted for practical use. The four chief types are as follows:—

(1) Jet Condenser.
(2) Surface Condenser.
(3) Ejector Condenser.
(4) Evaporative Condenser.

(1) *Jet Condenser.*—The first and most obvious method of condensing steam is by means of the jet condenser, so called because the exhaust steam from the engine passes into a chamber, where it comes into contact with a jet of cold water, which is sprayed into the chamber. The incoming steam mixes intimately with the jet of water, and an exchange of heat is rapidly effected, the steam condensing and the water rising in temperature.

We have seen that, in general, we require a large amount of water to condense a relatively small quantity of steam. This necessitates making ample provision for removing the great bulk of water from the condenser by means of large pumps which are generally called air pumps, from the circumstance that a portion of their duty consists in removing any air which has entered the condenser with the steam. The presence of air necessarily increases the pressure in the condenser, or, in other words, impairs the vacuum. It is of the utmost importance, therefore, to reduce the leakage of air as much as practicable.

(2) *Surface Condenser.*—The surface condenser was introduced in order to avoid the necessity for pumping out such large quantities of water from the condenser chamber. In this type of condenser

which appears to be superseding other types for plants working under normal conditions, the cooling water does not come into contact with the steam which it condenses. As generally arranged, the water circulates through a bank of brass tubes of some 15 millimeters external diameter, situated in a cast iron chamber. The exhaust steam enters this chamber, and impinges on the brass tubes. The heat of the steam is transferred through the metal walls of the tubes to the water which is continually circulating through them.

In a surface condenser, the temperature of the circulating water on emerging is somewhat less than the temperature of the condensed steam, so that more water is necessary than with a jet condenser. But this consideration is generally far outweighed by the circumstance that the condensed steam does not mingle with the cooling water. From this it not only results that the capacity of the air pumps may be much less, but also that the condensed steam, which is comparatively pure, may at once be used again as feed water for the boilers. This is an advantage which, with piston engines, has the drawback that the condensation is contaminated with cylinder oil. But with steam turbines the surface condenser leads to almost ideal conditions in this respect.

(3) *Ejector Condenser.*—Ejector condensers are only used in small plants. They are designed on the principle of impelling a spray of water past the mouth of the exhaust steam pipe. They possess the important advantage that no air pump is required, the only moving machinery being a centrifugal pump to deal with the circulating water. A good supply of water is essential for the successful working of an ejector condenser.

(4) *Evaporative Condenser.*—Where the temperature of the cooling water available for condensers is high, or where the cost for large quantities is prohibitive, it may be of advantage to install evaporative condensers. In this type of condenser the exhaust steam enters a series of cast iron tubes, over which a continual supply of water is kept trickling. The heat given out by the steam during condensation raises the temperature of the water, and evaporates a certain portion of it. The remainder of the water falls into a tank immediately beneath the tubes, and is in turn again pumped over the tubes. The amount of water evaporated may be some two-thirds of the weight of steam condensed. In order to obtain economically a maximum of tube surface, the cast iron tubes are sometimes corrugated.

Excellent descriptions and detailed illustrations of the foregoing

types of condensers may be found in text-books. From this point onwards we shall confine ourselves to considerations relating to surface condensers, since this is the type which is in by far the most extensive use at present.

By means of Table LIII. and Fig. 56, we are able to calculate the amount of water required for maintaining a given exhaust pressure, provided we have the necessary data as to the range of temperature change of the circulating water. As a rule we can ascertain the initial temperature of the available circulating water, but we shall not know how closely the final temperature of the circulating water may be brought to that of the condensed steam, and we must have recourse to test results. An exhaustive series of tests has been carried out by Allen,[1] and the author has, from Allen's results, deduced the curves in Figs. 57 to 59.

From Fig. 57 we see that when operating the condenser at the rate of 0,25 kg of steam per hour per sq dm of surface, Allen required 52 tons of water at an initial temperature of 20°, to condense one ton of steam at a pressure of 0,08 kg per sq cm. If we refer back to Fig. 56, we see that 52 tons of water at 30° would have sufficed to condense one ton of steam at the same pressure, if the final temperature of the water had been the same as that of the steam. From this we conclude that in a condenser of the type tested by Allen, the final difference in temperature between the water and the steam was in this instance $30 - 20 = 10°$. The dotted curves in Figs. 57—59 indicate the final difference of temperature between the circulating water and the condensed steam. The values are obtained in the manner outlined above.

Examining the corresponding curve in Fig. 58 corresponding to 0,38 kg of steam per sq dm per hour, we find that Allen required 57 tons of water to condense one ton of steam at a pressure of 0,08 kg per sq cm, and from Fig. 56 we calculate that the final difference of temperature is 11°. Again, from Fig. 59 it is seen that there were required 62 tons of water per ton of steam, and the final difference of temperature is 12°.

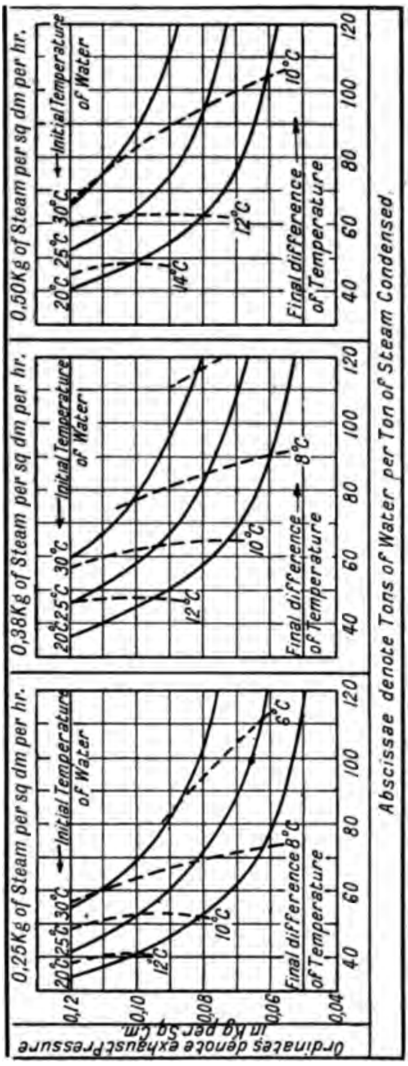
The condenser used by Allen in these tests had a total tube surface of 2800 sq dm. In one series of tests the average weight of steam condensed per hour was 0,68 tons or 680 kg. This is approximately equal to 0,25 kg of steam condensed per sq decimeter of tube surface per hour. Fig. 57 shows the result of these

[1] Surface-condensing Plants, by R. W. Allen, "Proc. Inst. Civil Engineers," vol. clxi., Feb., 1905.

tests, and Figs. 58 and 59 correspond to tests at 0,38 and 0,50 kg of steam per sq dm per hour respectively.

We thus see that the greater the rate of condensation of steam

Fig. 57. Fig. 58. Fig. 59.



Figs. 57—59. Relation between the Temperature of Condensing Water and the Exhaust Pressure.

Curves based on tests by R. W. Allen.

for a given condenser, the greater will be the final difference of temperature between the water and the steam. The result is inevitable, since the velocity of both the steam and the water in

Fig. 59 is approximately double the corresponding velocities in Fig. 57.

The curves in Fig. 60 have been deduced from one of the numerous series of tests carried out by Prof. R. L. Weighton.[1] The condenser had a tube surface of 570 sq dm, and the curves were found to apply to all tests up to 0,565 tons of steam per hour or 1 kg of steam per sq dm per hour. The divergence between the results in Fig. 60 and those in Figs. 57—59 indicate that the type and condition of the condenser largely affect the working results.

Surface condensers for steam turbine work should be proportioned

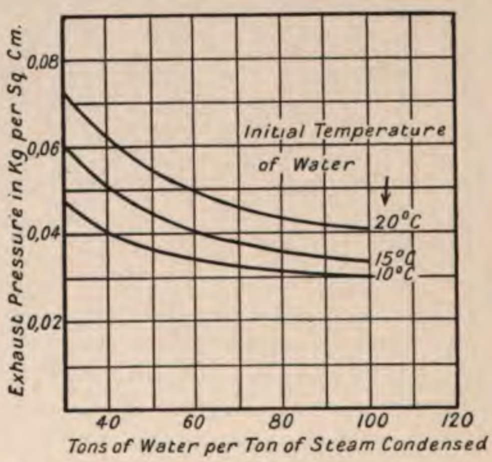


Fig. 60. Relation between the Temperature of Condensing Water and the Exhaust Pressure.

(Curves based on tests by R. L. Weighton.)

on the basis of some 40 sq dm of cooling surface per rated kw installed, as against some half this value with piston engines. With turbo-generating plants, to obtain a sufficiently low exhaust pressure it is often necessary to circulate more than 100 tons of water per ton of steam condensed.

Suppose that in the 270 million-kw hr-per-year plant outlined in Chap. III., we obtain 9 per cent. efficiency from coal pile to outgoing cables. Then during one year we must burn coal with a total calorific capacity of

$$\frac{270}{0{,}09} = 3000 \text{ million kw hr.}$$

[1] The Efficiency of Surface Condensers, by Prof. R. L. Weighton, "Proc. Inst. of Naval Architects," April, 1906.

Since good coal has a calorific capacity of some 8700 kw hr per ton, we shall burn $\frac{3000}{8700} = 0{,}345$ million tons of coal and we shall produce some 3,5 million tons of steam.

Hence we may require to circulate some 350 million tons of cooling water in condensing this steam.

One ton of water = 1000 liters (= 220 gallons).

Thus the annual circulation is 350 000 million liters, or

$$220 \times 350 = 77\ 000 \text{ million gallons.}$$

Allowing for 10 per cent. evaporation, there must be supplied per annum, some 35 000 million liters, or 7700 million gallons of make up water.

If this costs one penny per 1000 gallons, we have a charge of 7,7 million pence =

$$\frac{7\ 700\ 000}{240} = £32\ 000.$$

If coal costs 10 shillings per ton, we have an annual expenditure of £173 000 for coal.

Thus in this case the circulating water costs

$$\frac{32 \times 100}{173} = 18{,}5 \text{ per cent. of the cost of the coal.}$$

Were we to use piston engines, which would not be so greatly affected as regards decreased economy, by a slightly higher exhaust pressure, we could reduce this charge by half, and have, say, only 9,3 per cent. cost for circulating water, and a great reduction in capital outlay for condensers and cooling towers, smaller pumps and less energy consumed by pumps. On the other hand, the turbines will only require an outlay of some 5 per cent. less for oil.

Thus setting cost for coal at 100, we have—

	Piston Engine.	Steam Turbine.
Coal . . .	100	100
Circulating water	9	19
Oil . . .	8	3
Total . .	117	122

The higher the cost of coal and the lower the cost of circulating water, the less will be the advantage of the piston engine in this

respect. Often, however, the charge for circulating water is several pence per thousand gallons, whereas in the above example it has been taken as costing only 1*d*. per 1000 gallons.

Let us consider the case of providing a condenser for use with a steam engine or turbine working between an admission pressure of 13 kg per sq cm and with 50° of superheat, and an exhaust pressure of 0,1 kg per sq cm. From the steam tables we find that, at admission, one ton of steam contains 810 kw hr of energy. From Table IX. on p. 16, we see that the wetness factor of the exhaust steam should be of the order of 0,22. Hence for every ton of steam admitted to the cylinder at a pressure of 13 kg per sq cm, and superheated 50°, the exhaust mixture (at a pressure of 0,1 kg per sq cm) will contain 0,22 tons of water and 0,78 tons of steam.

The latent heat at the exhaust pressure is 663 kw hr per ton, hence for each ton of the exhaust mixture we shall require to extract $0{,}78 \times 663 = 518$ kw hr of energy in order to effect complete condensation. If the temperature of the circulating water is 30°, and if we estimate the condenser surface on the basis of condensing 0,5 kg of steam per hour per sq dm of cooling surface, then according to Allen's results, as given in Fig. 59, we shall require 89 tons of water per ton of steam. But for each ton of exhaust mixture, the net weight of steam is only 0,78 tons, so that there is required some $0{,}78 \times 89 = 70$ tons of water for each ton of steam passing through the engine.

CHAPTER VI

ELECTRIC GENERATING PLANT

Size of Unit.—There is no longer any question but that alternating current polyphase generating sets, each of large capacity, are preferable for large electric generating stations supplying energy to substations. During recent years the sizes of the individual units have rapidly increased until 5000 kw sets are now in extensive use and still larger sets are beginning to be employed. It is highly probable that in the immediate future, three-phase alternators, each delivering from 10 000 kw to 20 000 kw at their normal rating, will be successfully developed. These will be driven by steam turbines at speeds which may at first glance seem low, namely at speeds ranging from some 375 rpm for 10 000 kw sets, down to 250 rpm or less for 20 000 kw sets. It should, however, be remembered that the steam turbines on the *Mauritania* and the *Lusitania*, each turbine having a capacity for some 20 000 hp, are operated at a speed of less than 200 rpm when the vessel is proceeding at a speed of 25 knots. A land-type 10 000 kw turbo alternator would be driven by a steam turbine with a *maximum* capacity of well above 20 000 hp, and thus 375 rpm for such a set is still far higher than the speeds adopted for marine steam turbines of similar outputs.

With increase in the rated capacity, the employment of higher voltages becomes the more practicable, and 20 000 volts for a 20 000 kw set imposes no grave designing difficulties. A 20 000 volt 20 000 kw 25-cycle 250 rpm set will have 12 poles, a rotor diameter of some 4 meters (corresponding to a peripheral speed of 52 meters per second), and some 2 meters length of armature core parallel to the shaft. The length over the stator armature windings will amount to some 3 meters and the external diameter over the stator core will be some 5 meters. As external dimensions, some 6 meters diameter over the casing, and a length over end shields of some 4 meters, are reasonable estimates. This alternator will require some 15 tons of copper, 135 tons of electromagnetically effective iron, and 150 tons of materials entering into

the mechanical design. This aggregates 350 tons, or 17·5 kg per kilowatt of rated output. For a 6800 kw generating set, a pressure much above 11 000 volts (6350 volts per phase), entails considerable increase in the cost of the machine, and 11 000 volts may be taken as the preferable pressure. It is, however, highly probable that our gradually increasing knowledge of insulating materials will be accompanied by a substantial increase in the preferable pressure.

Insulation of High Pressure Machines.—Indeed the weakest point of present day designs of high tension machinery is the insulation. This state of affairs is so little realised that it is desirable to go further into the matter. Ten years ago the most experienced and conscientious manufacturers of alternators employed some 8 mm thickness of slot insulation on 10 000 volt machines. Half this thickness is now employed and with equally high safety factors. This progress has been accomplished chiefly with the poor guidance afforded by the almost culpably superficial tests of insulating materials heretofore considered sufficient. The consequent delay to the development of the electrical industry is, to those in a position to realise it, extremely vexatious. Those concerned in the management of most of the largest and best equipped companies engaged in building electrical machinery are very active in discountenancing rigorous insulation tests, and for obvious but short-sighted reasons. The obstacles which they place in the way of such tests greatly impede progress toward improved methods of insulation.

The technical policy of large electrical manufacturers is notoriously short-sighted. Too much enterprise is shown in taking orders at prices which, at the very best, can only permit of a profit when the design is cut very fine. If this is done with machines on which rigorous insulation guarantees have been undertaken, the manufacturer, on the occasion of the inspection tests, frequently resorts to discreditable tactics to avoid making the tests. The inspector is taunted with being unpractical, since it is alleged that, while the machine would withstand the tests, the insulation would be permanently strained. In cases where the specification has been intelligently drawn up in the customer's interests, and where the inspector insists upon its fulfilment, the manufacturer's designing engineers have an expensive object lesson which sometimes leads to a few desultory experimental investigations on insulating materials, and some of the results may make a sufficient impression to occasion the adoption of improved methods.

In another ten years we shall probably be employing a slot insulation thickness of 2 mm on 10 000 volt alternators, and with as high safety factors as were obtained with 8 mm ten years ago, and with 4 mm to-day. Had we, however, during the last ten years given anywhere nearly as much and as intelligent attention to the investigation of insulating materials as has been devoted to other aspects of dynamo design, we should already be in this position. The consequences of being able to reduce the thickness of the slot insulation are far reaching. We can take up part of the advantage in distributing the armature winding in more slots per pole. This will give us a better wave form, and greater immunity from the insulation troubles occasioned by higher harmonics and surges. As an alternative we can make the machine smaller and lower in cost, or else we can reduce the temperature rise or increase the output, or we can improve the pressure regulation in virtue of the greater proportion of the active belt which becomes available for copper and iron. But at present the slot insulation *thickness* is but a poor criterion of the quality of the machine from the safety standpoint. A certain manufacturer may be producing a better insulated 10 000 volt machine with a slot insulation thickness of 4 mm than another manufacturer is producing with 8 mm. The indifference to insulation investigations is deplorable. Almost any young man may, a few years after leaving a technical school, attain some approach to proficiency as a designer, so far as relates to the proportioning of the electric and magnetic circuits, as the problems involved have now been made more or less susceptible to technical analysis. Insulation problems cannot at present be solved in this way. The young engineer is thus for a time well content to be surreptitiously prompted by the winding foreman when it comes to drawing up the insulation instructions to be sent out later, probably to this very foreman. The foreman's *experience* is often considerable; the *judgment* which he may have acquired as the result of this experience, while it is sometimes sound, is rarely progressive.

When, as occasionally happens, the foreman's judgment is subsequently overruled by the young designer, the consequences are rarely encouraging, though, as they are often enlightening, they are apt to be attended by a certain amount of fitful progress. This description is not overdrawn, but it is a composite impression of the actual occurrences in a good many companies, and it should throw some light on the repugnance shown by manufacturers to the introduction of

other than the mildest insulation tests. It should, however, not require much reflection to understand that the adoption of more scientific methods of insulation testing would nevertheless be of an advantage to the manufacturer, which would far outweigh the expense incurred. The studied attempt on the part of large manufacturers and their subservient engineers to discredit the practice of subjecting machines to high voltage insulation tests and to substitute low factors of safety in specifications to which they tender, should not be permitted to succeed. If insulation tests are correctly made, the application of the prescribed high voltage will occasion no injury provided the insulation design is adequate, the material sound, and the workmanship intelligently supervised.

By careful tests and repeated examinations we may gradually raise the testing voltage to the specified amount, with the fairly certain knowledge that its application for one minute or for any other stipulated interval shall occasion no permanent harm to the machine. This, of course, is provided the insulation of the machine has been designed and carried out on a sufficiently liberal basis to justify the application of the specified voltage. Even with this provision, the immediate application in the first instance of the full testing voltage for the stipulated time would be a highly injudicious procedure, and should only be permitted after the careful and exhaustive tests at lower pressures. These tests should be made at gradually higher and higher pressures before the application of the final voltage is made. The testing engineer will thus assure himself from the analysis of the results of the preceding tests, and from his repeated inspection of the machine, that the full voltage can be applied for the stipulated interval without any risk of damage.

The operating engineer is in most instances only too eager to achieve the best results with the plant in his care. The fact that it has been customary to supinely wait for the insulation to break down is to a certain extent explained by the circumstance that the means for detecting the weakening of slot insulation prior to its attaining serious proportions have not been readily available, nor have the nature of the necessary measurements been at all obvious heretofore.

Even after machines are installed and placed in service, it is highly desirable to have tests of this nature carried out at intervals of, say, once per week and entered up in a log book. Such a procedure will enable the operating engineer to detect symptoms of any weakening in the insulation, long before these symptoms have

developed to such a point as to endanger the serviceability of the machine. These considerations are more important the larger the size of the machine, as a serious breakdown on a very large machine usually involves a great expenditure of time and money.

The Mechanical Design of Alternator Windings.—Another important point which is frequently overlooked in drawing up specifications for alternators relates to the requirements as regards the mechanical design of the windings. The construction of the end connections of the stator windings of a three-phase alternator should be such that they will withstand the following test:—

With the alternator running at normal speed and with the armature windings on open circuit, the field excitation should be adjusted to the value previously ascertained as necessary for obtaining normal voltage at the armature terminals when the machine is carrying its rated full load current. When this adjustment has been made, the armature should be abruptly short-circuited across the three terminals of its windings. For an instant, a current several times (often six or more times) in excess of full load current, will traverse the armature windings. This will rapidly decrease to some three times full load current and will remain constant at that value. On some machines, and under some conditions, the large instantaneous current may be read from an ammeter, but in other designs it will be of such brief duration as only to be detected by means of the record from an oscillograph. Except as a matter of interest, it is not necessary for the purposes of the test that this current should be determined.

During and subsequent to this test, the stator end connections should be carefully inspected. Should no temporary or permanent displacement of the end connections be detected, the construction may be considered satisfactory. Otherwise, the construction should be so modified as to enable the machine to satisfactorily withstand this test. The machine can then be relied upon to sustain no mechanical injury as the result of short circuits on the line.

It is, of course, desirable that a machine, when its fields are excited to the normal value, as defined above, should withstand the stress consequent upon being thrown in parallel with other machines already themselves operating in synchronism, when in precisely the opposite phase from these other machines, and modern machines will often withstand this test. But such an extreme condition could fairly be pronounced unreasonable, and would obviously

only arise through misuse of the machine, even though the occurrence might be accidental.

The test above prescribed would, however, ensure that the machine would not be liable to sustain injury when thrown into phase with other machines, at an instant when its own phase differed by a reasonable amount from the phase of the other machines, as inevitably occurs repeatedly in the ordinary course of operation of all plants employing machinery of this kind. This does not signify misuse of such machinery.

If it appears doubtful whether a completed machine will withstand this test, and if it is desired to avoid injury to the windings in ascertaining the mechanical sufficiency or otherwise of this feature of the design, then the tests may be carried out by first short circuiting the machine with some 20 per cent. of normal excitation and then repeating the test, employing 10 per cent. higher excitation each time. One may thus determine the value of the excitation at which the first slight mechanical displacement of the end connections occurs and thus avoid the risk of the serious injury to the machine which might be occasioned by short circuiting it in the first instance with the excitation adjusted at a high value.

These tests may disclose the necessity for an improved mechanical construction of the end connection supporting arrangements. When such contingencies have not been foreseen, it is generally extremely difficult to incorporate adequate arrangements, and extra insulation becomes necessary in isolating the end connections from the additional supporting brackets or flanges. Hence short circuit tests of any such re-modelled constructions should be followed by insulation tests and by heating tests, in order to determine whether the design, after finally withstanding the short-circuit tests, still complies with the insulation and heating requirements.

It is desirable to require that the short circuit test with normal excitation shall be repeated for a reasonable number of times and that no displacement of the end connections shall be thereby occasioned.

Further Mechanical Tests of High Speed Machines.—On account of the high peripheral speeds of turbo-driven alternators, rather small mechanical factors of safety are apt to be employed. A high speed alternator should be required to withstand a test consisting of running it for five minutes at 50 per cent. in excess of normal speed. Alternators to be driven from water wheels are sometimes required to withstand a test at double normal speed. The author has had

occasion to subject 5000 kw alternators to this test. In one instance the peripheral speed reached 115 meters per second. The bearing and windage friction was then some 10 times that corresponding to normal speed, and although, of course, the alternator was driven at no load, and unexcited, quite elaborate testing arrangements were necessary.

It is as well to keep this in mind, as such arrangements, if not planned in advance, occasion delays which are vexatious to all concerned. The inspecting engineer recognises that he is in duty bound to have the tests carried out, and his position should be respected by the contractor. Almost invariably, however, his task is rendered very difficult by representations that the requirement is unreasonable, and it is often plainly intimated that he is displaying poor judgment in refusing to pass the machines without this or some other test. Contractors should realise that it is only common courtesy to an inspector to give him every reasonable facility for conscientiously carrying out the specified tests. If certain conditions of the specification are irksome to them, they have only themselves to blame for taking on the contract. To trust to Providence that a docile inspector shall be allotted to them is to harbour the dishonest intention not to live up to the specification.

Unfortunately most contractors are, in the writer's opinion, and as the result of considerable experience, inclined to resort to browbeating any inspecting engineer who acts right up to his clients' interests, and it is to be feared that this state of affairs is in no small measure due to the docility and inefficiency of most inspecting engineers. The inspecting engineer must, of course, abstain from requiring unreasonable tests, and he must stand prepared, if in his opinion certain clauses in the specification are unreasonable and not necessary in guarding his client's interests, to place these facts before his client with a recommendation that he be authorised to waive these tests. But this is a long way removed from taking sides with the contractor, letting the specification go by the board, and blindly passing the machinery. That, and that alone, is the attitude required by some contractors, and they will go to any length to render untenable the position of a conscientious inspecting engineer who, if aware of this state of affairs in the first place, would only undertake the inspection on the distinct assurance from his client that he quite understood the situation and required that the machinery should be subjected to a serious inspection. Unfortunately, however, the state of affairs only becomes untenable at a

later stage and the inspector is often dismayed to find actual collusion between contractor and client. Thus the contractor may be an influential shareholder in the company for whom the client is acting, or the client, in some other capacity, may be dependent upon the contractor for a considerable proportion of the business turned over to him in this other capacity. Such relations are far from rare, and where they exist, the business is a farce so far as relates to specifications and tests. The various scenes in this farce are, however, generally carried through with every outward appearance of seriousness, for the edification of the lesser shareholders in the various related enterprises.

No discerning engineer of experience will fail to recognise these as representative of the conditions amidst which, or, rather, notwithstanding which, serious engineering enterprises are being carried through. The resulting excessive capital outlay incurred before any large engineering undertaking is completed is frequently less a direct burden on the original investors than on the public at large, upon whom the burden is ultimately shifted. As instances of the more or less direct consequences of the handicap thus imposed upon important engineering undertakings may be mentioned the high charges for electrical energy in London and Paris, the necessity to increase the fares on the tube railways, and the continued postponement of the electrification of the suburban sections of the main line railways terminating in London.

In the first and second of these instances the higher rates are required to a far greater extent for the purpose of meeting the charges on the wasteful and misdirected initial capital outlay than they are required for meeting the operating costs. The continual delay in railway electrification in a field where it would be of great advantage is in large measure due to the distrust created in the minds of railway directors by the conflicting views regarding the merits of single phase traction, and this delay is likely to be further protracted when the results obtained on the single phase roads now building are analysed. These results will be of so distinctly unsatisfactory a nature as to reflect seriously on railway electrification in general. In a subsequent chapter dealing more specifically with systems of electric traction, the grounds for dissatisfaction with the attitude of the advocates of the single phase system are more specifically set forth.

The Relative Merits of Generating Sets of Various Types.—Gas-engine-driven polyphase generators are in some respects

unfortunate combinations from the dynamo builder's standpoint. The disadvantages relate chiefly to the parallel running of such sets, and to the operation of sub-station apparatus therefrom. The uniformity of angular rotation must first be maintained as high as possible, and the means to this end at the gas engine designer's disposal have to be supplemented by very great additional flywheel capacity. Assuming this to be provided, the next step consists in sacrificing several per cent. of the efficiency of the polyphase generator owing to losses in amortisseurs employed in order to still further reduce the lack of uniformity in angular rotation. But the combined set will even then be distinctly deficient in this respect, and another feature should be introduced, namely, a very low periodicity, and this periodicity should be lower the lower the speed of the type of gas engine employed. This last feature, namely, low periodicity, possesses no especial disadvantages; it leads to a better design of generator with fewer poles and higher efficiency, and also to better conditions in the transmission line and at the sub-station. Yet it is the one step least likely to be resorted to, and for no very good reason, so far at least as relates to traction work. The persistency in refraining from low periodicities when justified by circumstances, such as the parallel operation of polyphase generators from gas engines, and even from large slow-speed steam engines, is really a remarkable phenomenon in modern electrical engineering, but there are at length signs of a more satisfactory attitude on this question.

Comparatively few installations with parallel-operated polyphase generators, driven by gas engines of large capacity, are in service, and it would seem unwise to disregard the lessons learned on plants employing their nearest equivalent, namely, large slow-speed steam engines with scanty flywheel capacity. Experience with such sets has shown the wisdom of taking all practical precautions to improve the uniformity of angular rotation, and, for a given obtainable angular uniformity, to improve the electro-magnetic uniformity by employing low periodicity. Thus, for a given degree of angular uniformity at a given speed, the electro-magnetic uniformity will be inversely proportional to the periodicity. For example, the percentage electro-magnetic displacement will, for a given speed, be just twice as great in a thirty-cycle generating set as in one for fifteen cycles per second. This is an indisputable broad fact, and is altogether independent of the quality of the gas engine or steam engine from which the electric generator is driven. Perfect satisfaction could,

doubtless, be obtained with polyphase current, gas-engine-driven generators for parallel operation, were a sufficiently low periodicity adopted, and motor generator sub-stations could be operated therefrom. Should all the other conditions be favourable, namely, were there employed fairly high-speed gas engines with the best obtainable inherent uniformity of angular rotation, ample flywheel capacity and very low periodicity, rotary converters might even be used instead of motor generators were there sufficiently good reason for employing them, and were they not required to have especially high commutator voltage.

Rotary converters, owing to their somewhat lower first cost, high nominal efficiency, and to their economy in floor space, continue to be employed in sub-station equipment in spite of their many undesirable properties. The question of motor generators *versus* rotary converters has received a great deal of consideration. One point, however, which is still generally overlooked, is that a much greater cost for high-tension cables is required when rotary converters are employed in sub-stations, in order to obtain any approach to a satisfactory automatic control of the commutator voltage. This is a most important point to keep in mind from the commercial standpoint when we consider the proportion which the cost of high-tension cables bears to the total cost in the average installation for traction.

Engineers cannot afford to overlook the economies which may be effected in that direction by employing motor generators instead of rotary converters. For with motor generator sets the cables may be given the minimum copper cross section consistent with thermal conditions, as the synchronous motor in the sub-station, if suitably designed, will carry high overloads at much less than normal voltage, as will also the rotary converter, but with the latter the commutator voltage, even with a liberal compound winding, cannot be maintained high when the drop in the transmission line is great, nor can freedom from "surging" or "hunting" then be ensured.

Returning to the question of the field for gas engines for driving electric generators, we have seen that, with polyphase machines, satisfactory results can only be obtained by arranging that all the other conditions shall be favourable to good electro-magnetic uniformity. Large *continuous-current* generators may, however, be designed on economical lines for direct coupling to slow speed gas engines. It is true that even a continuous current generator may be sensitive at the commutator as the result of insufficiently uniform angular rotation, but for low speeds there is no difficulty in designing even

the largest continuous-current generators (and for high voltage if desired) with such excellent commutating properties as to have ample margin in this respect; and such designs may be thoroughly normal, not requiring any undue outlay for material and construction. For continuous-current generators to be driven from *high speed* gas engines the case is somewhat different. For the customary high speeds for such engines, the difficulties are by no means great as regards the securing of satisfactory results, but such results can only be secured by considerable liberality in material, so that the high speed continuous-current generator, if equally satisfactory in performance, will for its output be but little less expensive than its low speed equivalent; and the difficulties are greater the higher the rated speed and output. In other words, a satisfactory machine of small output could have a fairly high rated speed without being disproportionately expensive per unit of output for that speed. When both speed and output are high, a gas-engine-driven continuous-current generator should be liberally designed and consequently relatively expensive. Slow-speed steam engines practically always have amply sufficient angular uniformity for the purposes of driving continuous-current generators, and the slow-speed steam engine may be regarded as the ideal engine for this purpose, for the most favourable condition for obtaining satisfactory commutation from large continuous-current generators is low speed. Where, however, high speed is absolutely required, continuous-current generators of large capacity require to be designed on lines leading to nearly as great cost as for the same rating at low speed.

Up to fairly high values for the speed, however, the design and operation of *polyphase* generators are rendered very much more satisfactory the higher the speed. Polyphase generators of large capacity for direct driving from low-speed engines are less satisfactory the higher the frequency. As for gas-engine-driven polyphase generators, they may be made fairly satisfactory if required for low periodicity. The higher the periodicity, the more important for polyphase machines does high speed driving become. The so-called "high-speed" and "quick revolution" engines have a range of speeds admirably adapted for driving alternators of corresponding outputs, and for any periodicity which would nowadays be chosen. But even for these cases the design and operation of the alternators are generally better when for low periodicity, which is, however, then much less essential to good operation than with low speed sets, where it becomes all-important.

Coming next to steam turbine speeds, these are at present undesirably high even for polyphase machines, and owing to the small number of poles, such as bi-polar and four-pole machines, and the designing difficulties, especially with reference to avoiding undue temperature rise, associated with machines of large capacity with these very small numbers of poles, the tendency is to adopt rather higher periodicities, and thus employ more poles where large steam-turbine-driven polyphase generators are required. And this is justifiable until such time as shall suffice for the evolution of considerably slower speed steam turbines, but it should be an additional consideration weighing against employing rotary converter sub-stations on systems with steam-turbine-driven generators, except possibly where the rotary convertor's commutator voltage may be low or its rated capacity small, and these conditions are rarely encountered in modern traction work.

In fact the *present* customary continuous-current voltage is too low, and were it not for the high degree of standardisation to which the large electrical manufacturing companies who usually undertake these schemes have brought their traction systems and apparatus, and for local regulations and prejudices, a good deal could be said in favour of employing, for traction work, a continuous current pressure of 1200 volts, or even much higher pressure, in place of the time-honoured limit of 650 volts. This would materially reduce the cost for transmission copper, and would lead to little, if any, difficulty in the design either of generators, motors, or controllers; it could be fairly maintained that, from the designer's standpoint, the advantages would generally offset the difficulties. It would, it is true, make low speed engines more than ever desirable for driving the machines at the power house in cases where the latter were to directly generate continuous current; and where the power is there generated in the form of polyphase energy it would lead to rather lower speed, and hence to somewhat more expensive motor-generator sets at the sub-stations in the interests of a good design for the secondary member—the continuous current generator, and it would weigh to a still greater extent against the use of rotary converters. But large high voltage low-speed continuous-current generators, whether for the power house or for the secondary of the sub-station sets, may be economically designed for excellent performance, and in fact *more* economically, so far as relates to their commutators, in proportion to the increased voltage, since the amount of active material in a commutator is, to a certain extent,

proportional to the current to be collected, as are also the I^2R losses and brush friction losses. Hence the high voltage machine is the more efficient, not only on account of the reduced commutator losses, but also to the extent of the somewhat reduced field copper and armature core losses, since the number of poles is, preferably, considerably less. The altered conditions in the design of the tramcar motor would not off-set one another so greatly in favour of a 1200 volt machine; there would, in fact, be little if any choice, but the difficulties of design in controllers for heavy traction work are in proportion to the currents to be carried, and hence would be less—at any rate they would not be increased—by the adoption of 1200 volt motors. The same applies to collecting ploughs, trolleys, circuit-breakers, and auxiliary apparatus generally, and in heavy railway work *at least* 1200 volts will certainly be employed. The progress made in the manufacture and application of insulating materials generally is ample to justify the use of much higher pressures for such work, without entertaining any misgivings on this score.

In the light of the considerations touched upon above, it will be plain that the great economies now known to be possible by the employment of gas engines may, so far as their employment in driving electric generators is concerned, be most satisfactorily used in connection with large, low-speed, continuous-current dynamos. With the present state of advancement in dynamo design, excellent machines for this purpose may be provided and at normal cost. Continuous current transmission from the central station at moderately high pressures from such units is, with the increasing magnitude of traction projects, very desirable indeed, and the area to be economically fed from a single power house may thereby be greatly increased.

Development on the line of steam-turbine-driven sets will, however, probably be chiefly confined to *polyphase* generators, which, at a not very low periodicity, will supply power to motor generator sets in sub-stations. These motor generator sets should, from the standpoint of the best design for their primary member, the synchronous or induction motor, be of rather high speed, but for the secondary member, the continuous current generator, the design will be better the lower the speed, especially if a high voltage is required at its commutator. Hence an intermediate speed should here be employed.

It is not generally realised that the high-speed steam engine

generating set is not so very much heavier than the steam-turbine-driven set. This may be seen from Fig. 61, where comparative curves are given. Although the use of turbine sets effects a saving in floor space and foundations, the capacity of boiler plant and auxiliary steam plant is not reduced below that required for the best piston engine plant, and consequently the total saving in cost of power house and equipment is by no means in proportion to the reduced size of the generating sets. In Fig. 62 are given some

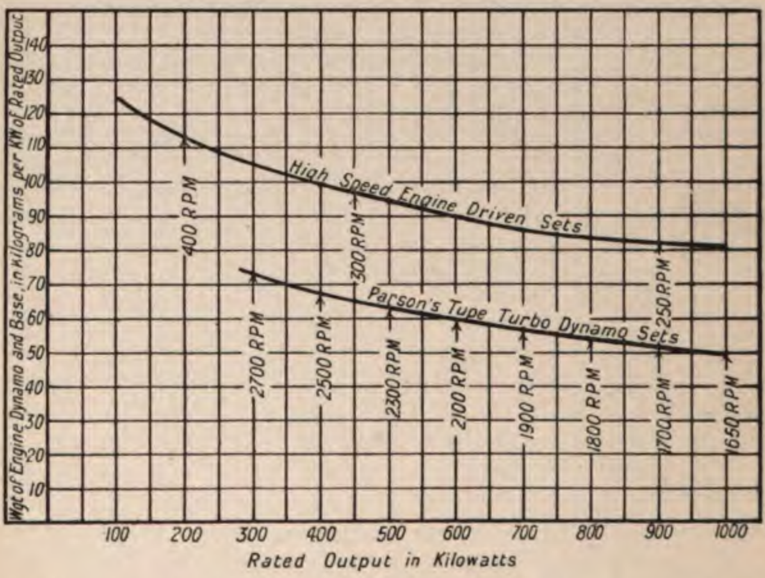


Fig. 61. Comparison between Weights of High-speed Engine Driven Generating Sets and Parson's Type Turbine Driven Generating Sets.

curves representing roughly the range of speeds of sets employing as prime mover the Parsons type of steam turbine, the high-speed engine and the low-speed engine. There is also added a curve toward which progress in design should gradually bring the steam turbine. Even this is rather high for satisfactory polyphase alternators, and offers still graver difficulties in the design of continuous-current dynamos.

The author is not of opinion that, in large electric generating stations, the main generators will, except in rare instances, be of the continuous current type. In sub-stations, however, the generators

of motor generator sets will, in the majority of cases, be provided for the purpose of obtaining a continuous current supply. It is important to grasp the significance of this distinction. Electrical energy in the alternating current form is most suitable at the main generating station, and in the high-tension transmission system; continuous current energy is superior for distribution purposes.

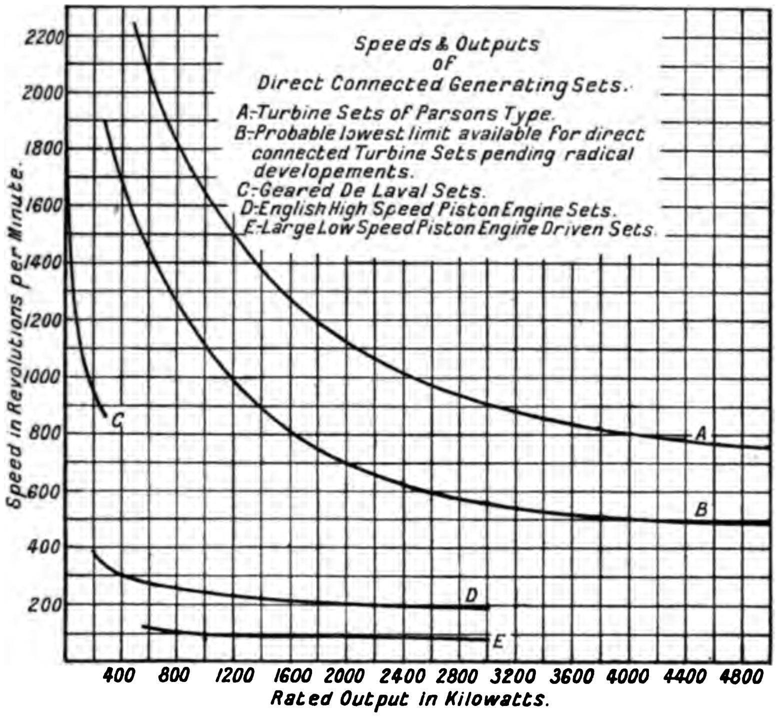


Fig. 62. Relation of Rated Speeds and Outputs of Direct-connected Electric Generating Sets.

This leads to no difficulties whatsoever; on the contrary, the readiness with which electrical energy can be transformed from one of these forms into the other is one of the chief features which have contributed to the rapid developments in electrical engineering.

One of the chief reasons for the superiority of continuous current for distribution relates to the superiority, as regards secondary voltage regulation, of motor generators as compared with stationary transformers. Other important features relate to the more effective

means for speed variation afforded by continuous current motors, as well as to their superiority in the matter of starting with heavy torque. New developments may, of course, at almost any time quite reverse this order of things; nevertheless, developments of the last twenty years have very consistently tended toward these general conclusions with regard to the respective fields of usefulness of these types of electrical machinery.

CHAPTER VII

THE DESIGN OF GENERATING STATIONS

In the general design of stations containing generating apparatus attention should be directed to the attainment of the maximum simplicity consistent with economy. The underlying plan should be such as to permit of systematic extensions on the lines adopted for the first sections constructed.

A modern building for a generating station, or for a sub-station, usually consists of a steel framed structure of sufficient strength to support the girder rails for the travelling crane. The walls are either filled in with brick, or they are of corrugated iron. In either case, in a well-designed building, in order to permit of systematic extension, both the boiler house and the engine house should be provided with temporary end walls which may be of corrugated iron.

The main building of an electric generating station comprises a boiler house, an engine room, and, in cases where the main switchboard is not located in the engine room, a separate switch room.

Provision is also usually made for coal storage, the capacity of the store depending on the facility for obtaining coal. Where the prompt delivery of an ample supply can be relied upon, the need for providing great storage capacity is decreased. There will, in addition, be a number of minor buildings consisting of general stores, repair shops and offices. The location of these minor buildings should be such as not to interfere with any extension to the main buildings.

Choice of Site.—For a power or lighting system the site should preferably be chosen at the centre of the area of supply. The selection of the site may, however, be influenced by several factors, among which are the facilities for the supply of coal and water, and considerations relating to the price of land and to the rates. It is desirable to choose a site near a railway, canal or navigable river, as this permits of coal delivery at a minimum cost. A situation adjacent to a river or canal is also convenient if the condensing water or the feed-water may be drawn therefrom. The facilities for condensing water supply may also have some bearing on the choice

of steam generating plant, the absence of a cheap and plentiful supply of water for condensing purposes constituting a factor in favour of using piston engines. This matter has been dealt with in Chapter IV. If the undertaking is in connection with a refuse destructor plant, the site should not be too far from the area from which the refuse is collected, since the cost of cartage is thereby reduced. On the other hand, a destructor plant constitutes a nuisance, and should be at a considerable distance from thickly settled districts. Since, however, it is now amply demonstrated that real economy is rarely, if ever, secured by the employment of refuse as a fuel, these considerations have but slight importance for electrical engineers.

The rates and the price of land in a large town rarely vary greatly in those districts where an electric generating station is likely to be situated. In cases where land is expensive, it is desirable to employ a compact design for the station. High-speed generating sets offer, in this respect, considerable advantages over slow-speed sets. The saving in floor space effected by steam turbines is of importance, although, as we shall see, it has not so great an influence on the total space occupied by the whole of the plant and buildings as might at first sight be supposed. The shape of the site affects the design of the buildings for the main plant. Provided the site is of convenient rectangular shape and of ample dimensions, the design of the buildings generally follows certain standard lines.

General Arrangement of Station.—With a view to obtaining a maximum of simplicity the plant should be so laid out as to provide the energy with a direct and short path through the station from the coal bunkers to the outgoing feeders. For this purpose the boiler house is arranged alongside the engine room, the coal is delivered to the boilers at the outer side of the boiler house, and the switchboard is arranged along the opposite side of the engine room. This is a simple arrangement which usually works out well. A diagrammatic outline of this arrangement employing a single boiler house and engine room is given in Fig. 63. The coal is delivered to the boiler house at the left-hand side by trucks coming from the point of delivery, whether a railway siding or waterway, and running alongside the boiler house. Where hand firing is employed, the coal is usually shot directly upon the boiler house floor. Where mechanical stoking is employed, the coal is delivered to hoppers in the roof of the boiler

house and is fed through chutes directly down upon the grates. The coal is usually fed into the hoppers by means of an endless conveyor running the whole length of the boiler house. The coal conveyor generally comprises an endless belt or chain, the former carrying the coal in a continuous stream and the latter carrying buckets containing the coal. In the latter type, the conveyor delivers the coal as it travels along above the hoppers by tripping the buckets at suitable points. The empty buckets pass along the bottom under the floor and may be employed for removing the ash.

A station following these general lines is shown in Figs. 64 and 65.

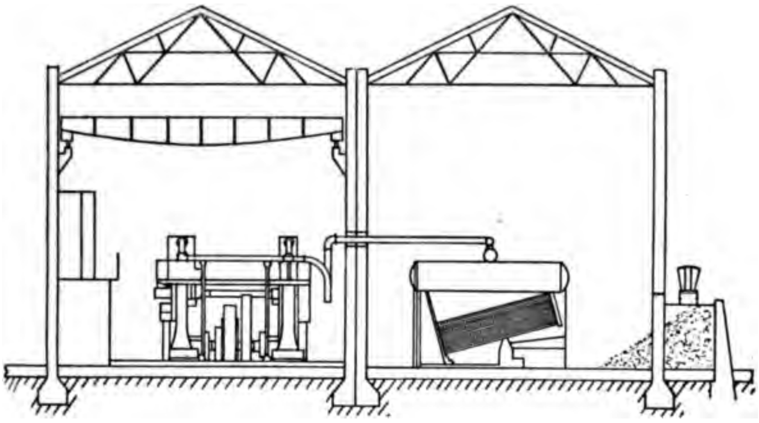


Fig. 63. Section of a Typical Power Station, with Slow-speed Vertical Engines.

In this case there is a double row of boilers and engines. The coal hoppers may be seen in the roof of the boiler house. Trucks running in the basement below the boiler house floor are employed for disposing of the ash and clinkers. The double row of boilers and engines make it necessary to employ excessive lengths of steam piping, and this would be reduced if two boiler houses, one along each side of the engine room, were employed, as could be done by duplicating Fig. 63. This arrangement is quite practicable, especially when the switchboard, as in Figs. 64 and 65, is arranged at one end of the engine room instead of along one side. The disadvantages of such an arrangement, however, outweigh this slight gain, since two buildings instead of one would be necessary for the boilers. Two coal conveyors would also be required and a larger boiler house staff.

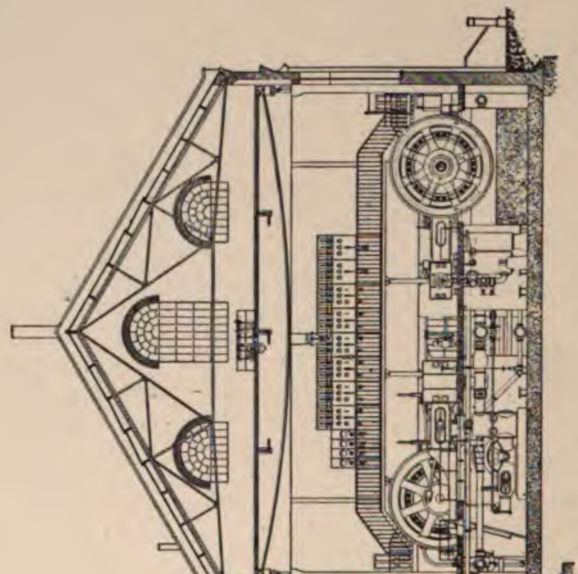


Fig. 64. Central London Railway. Sectional Elevation of Power Station.

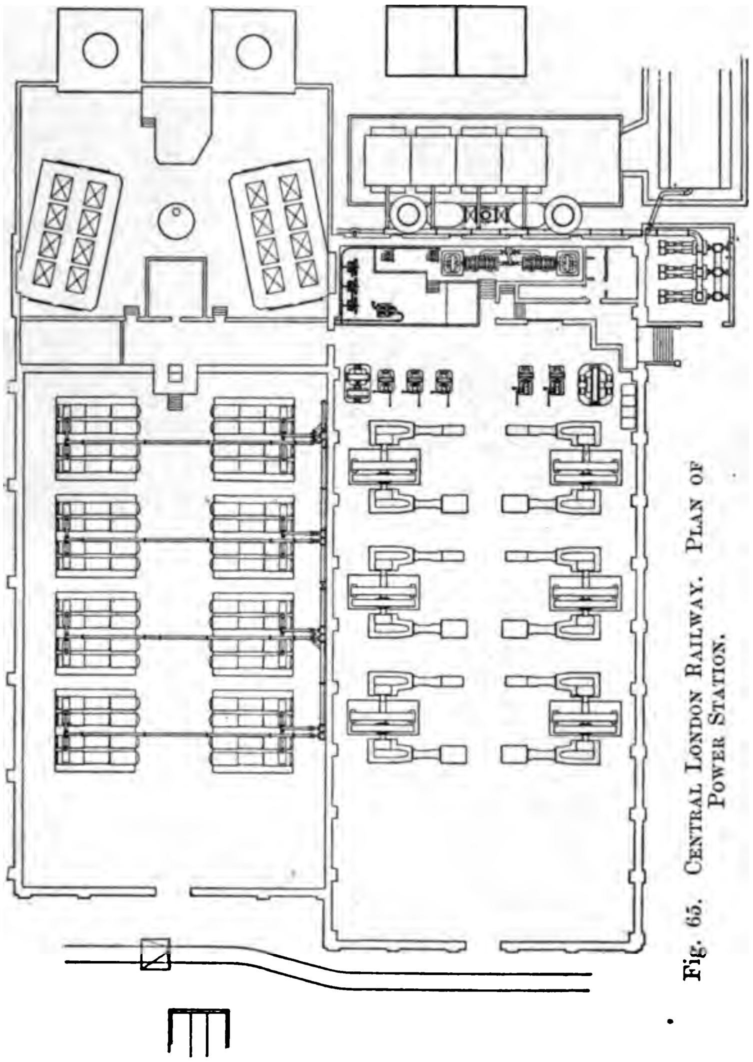


Fig. 65. Central London Railway. Plan of Power Station.

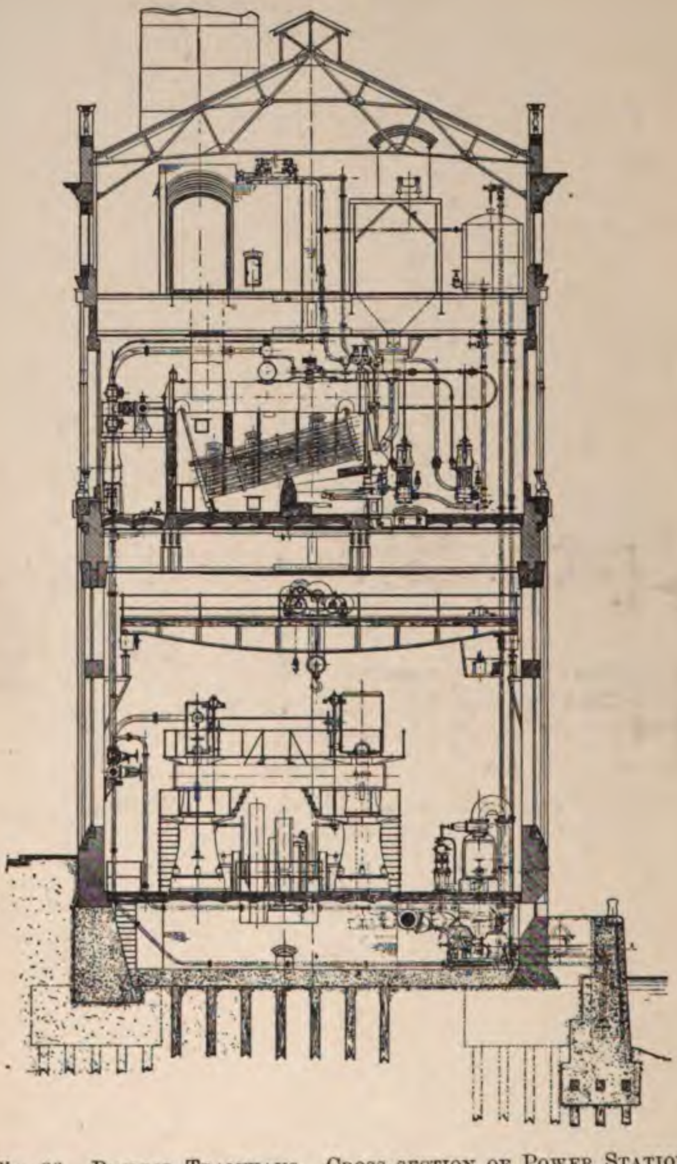


Fig. 66. Bristol Tramways. Cross-section of Power Station.

The two batteries of boilers would also be isolated unless they were connected by pipes running across the engine room at either end, or running under the engine room. This lay-out is, however, useful for steam-turbine stations where a large amount of boiler space, as com-

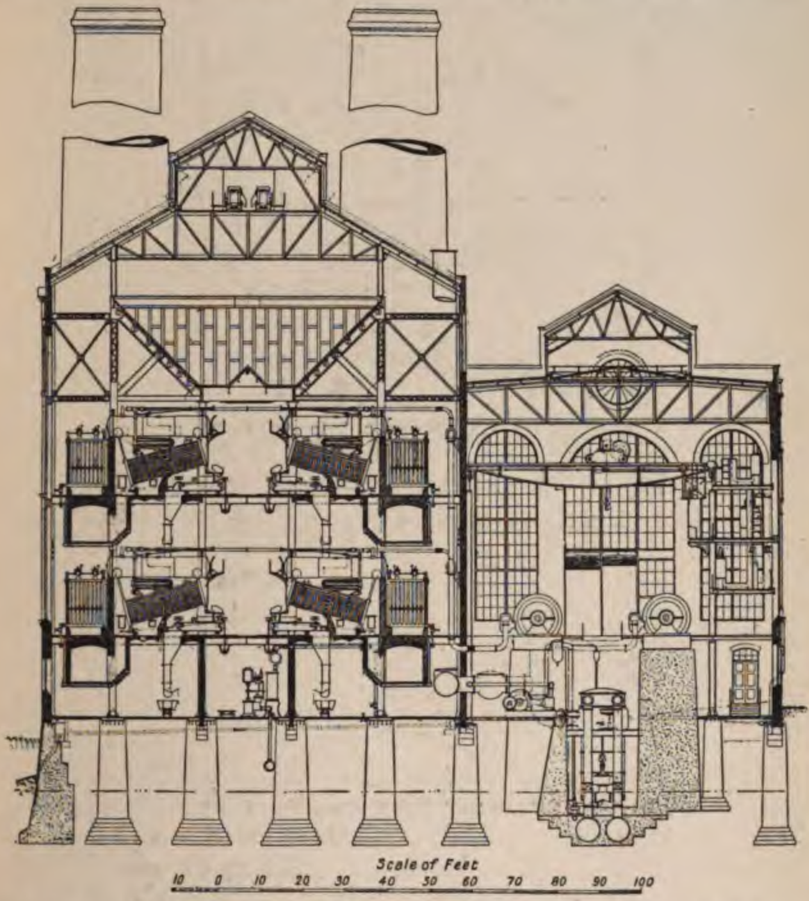


Fig. 67. Cross-section of Chelsea Power Station of the London Underground Railways Co.

pared with engine room space, is required. The plan is employed in the station illustrated in Fig. 79.

The general lay-out is necessarily affected by the shape of the available site. The arrangement diagrammatically indicated in Fig. 63 is suitable for a long and narrow site, and that in Fig. 64 when the site is shorter and wider. An irregularly shaped site affects

the systematic arrangement of the plant, and not only complicates the provisions made for dealing with the coal, but also disadvantageously affects the design of the steam piping. In stations in expensive districts in the centres of towns the boilers have occasionally been placed above the engine room as indicated in Fig. 66. This plan requires the provision of a very strong and expensive structure in order to stand the weight of the boilers on the upper floor.

Steam Turbine Stations.—In stations employing reciprocating engines, the boiler and engine houses are much of the same size, as will be seen from Figs. 63 and 64. Where, however, steam turbines are employed, the space required for the engine room is considerably less, and consequently the engine room, as compared with the boiler house, is relatively small. For this reason difficulty is encountered in arranging suitable accommodation for a sufficient number of boilers for the turbines. Hence in steam turbine plants considerable departures from the arrangements found in piston engine stations are necessary. The two principal departures are double-decked boiler houses and the use of a number of short boiler houses arranged at right angles to the engine room. Fig. 67 shows a steam turbine station with a double decked boiler house, and in Figs. 68 and 69 an instance of the second arrangement is shown.

The latter plan leads to what is known as the "complete unit" system of grouping of plant. A unit in Figs. 68 and 69 consists of one generating set with its condenser and its own battery of boilers. This principle has by some engineers been carried to the extreme of making each of the "units" entirely isolated from the others. In this case any one set of boilers may only be run on one particular engine.

It would usually be better practice, so far as relates to flexibility, to have all the boilers piped on to a common steam range with isolating valves between each battery of boilers. Thus under ordinary conditions each battery of boilers would supply its own engine, but any set of boilers could, when required, be run on any engine. Such a plan is practically identical with that shown in Fig. 70, which is a plan of the Central Electric Supply Co.'s Marylebone station, where the generating apparatus consists of high-speed vertical steam engine plant with Climax vertical boilers. The boilers are piped in rows at right angles to the engine room, and a chimney is provided for each group of boilers.

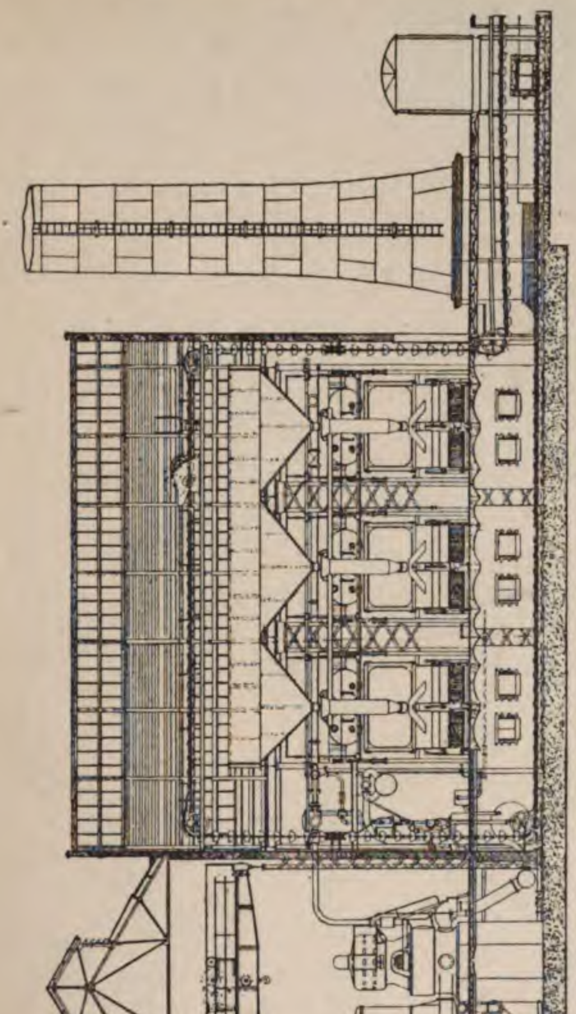


Fig. 68. Sectional Elevation of Thorn Hill Power Station of the Yorkshire Power Co.

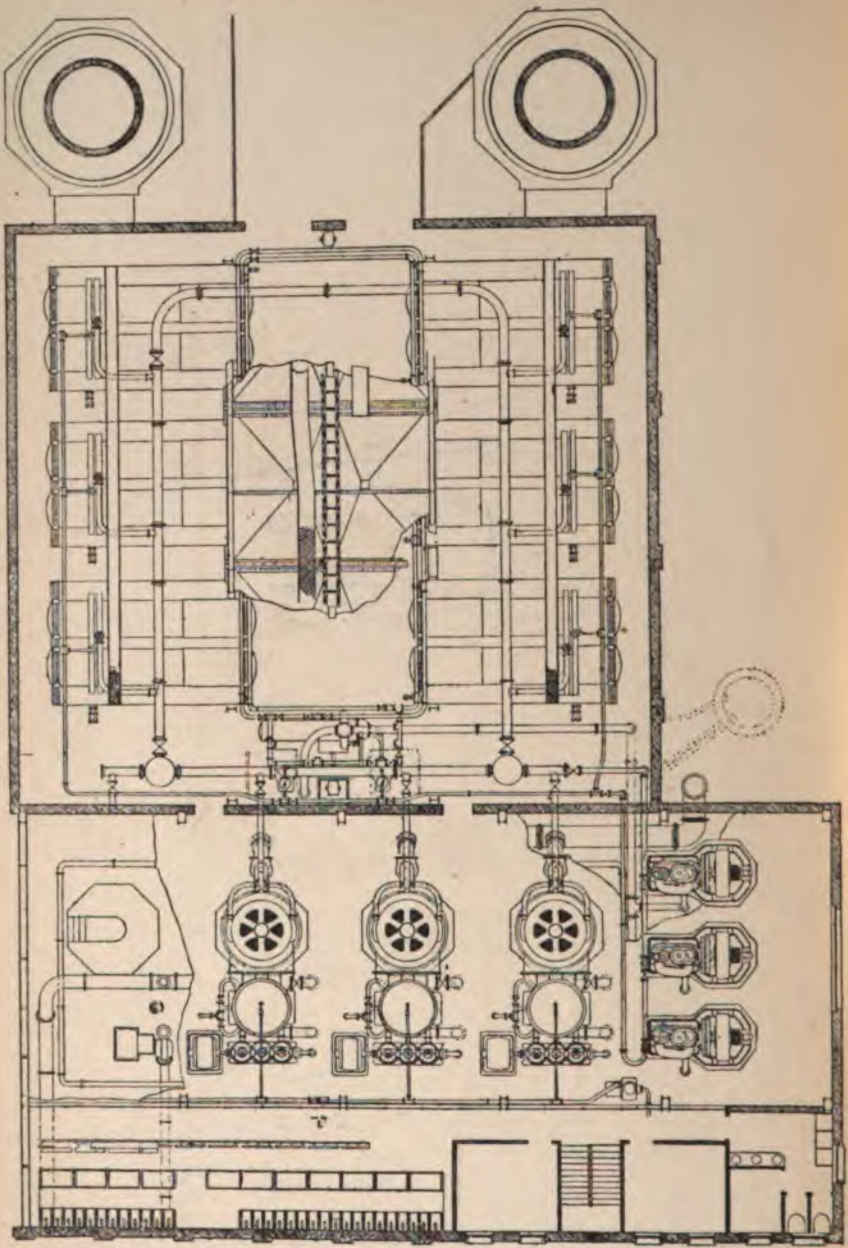


Fig. 69. PLAN OF THORN HILL POWER STATION OF THE YORKSHIRE POWER CO.

Figs. 71 and 72 illustrate a systematic design with Parsons urbines and Lancashire boilers. Since in this case the oilers are long and narrow, the turbines may be laid up fairly ose together, giving a compact and convenient arrangement.

The designs now described cover the leading plans for boiler ad engine house plant. The arrangement of the auxiliary

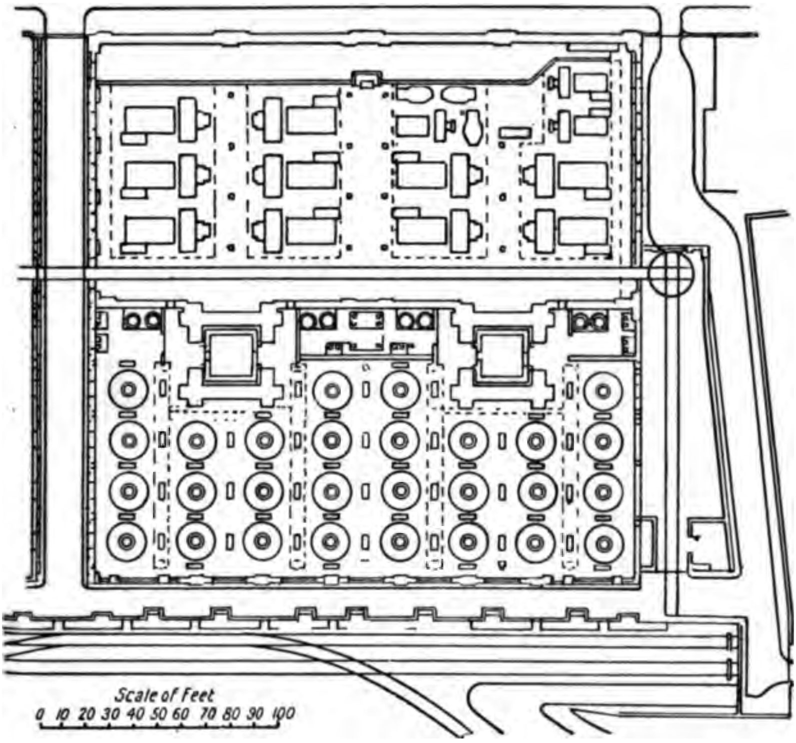


Fig. 70. Plan of the Central Electric Supply Co.'s Marylebone Station.

plant does not greatly affect the general scheme, but is more a matter of detail.

Size of Boiler House and Engine Room.—Some figures relating to the size of buildings and the space occupied by various types of generating plant will now be given. Table LIV. embodies particulars of the engine rooms and generating machinery for forty-eight power stations.

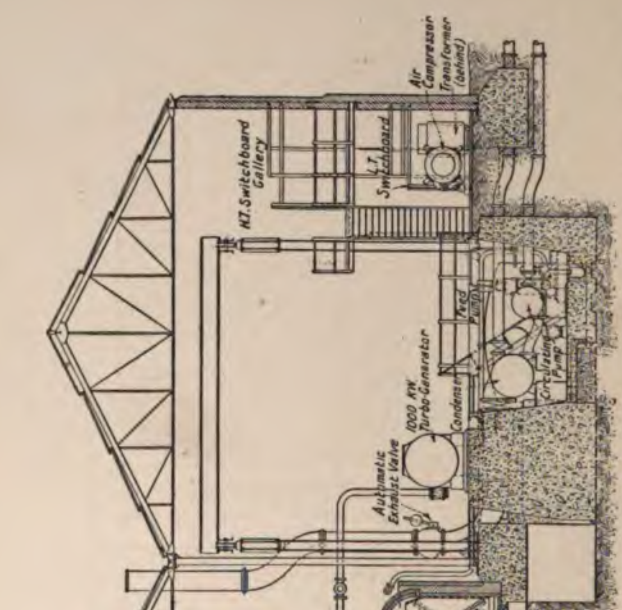


Fig. 71. Cross-section of Engine and Boiler Rooms of Great Eastern Railway's Generating Station.

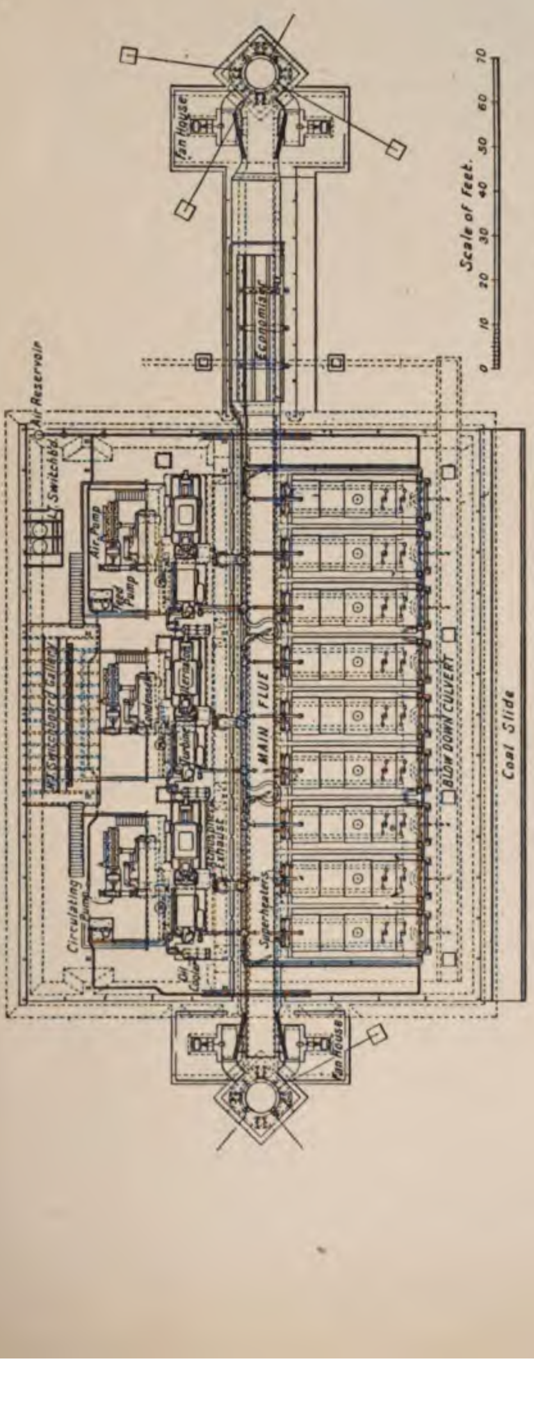


Fig. 72. Plan of Generating Station of Great Eastern Railway

The data have been grouped with reference to the types of engine as follows:—

(a) Horizontal slow-speed steam engines.
(b) Vertical slow-speed steam engines.
(c) Vertical high-speed steam engines.
(d) Steam turbines of Parsons type.
(e) Steam turbines of Curtis type.
(f) Gas engines.
(g) Hydro-electric installation.

Some interesting and useful conclusions may be drawn from Table LIV. Thus the extent to which the engine room space per kilowatt of rated capacity is affected by the type of engine may be ascertained. Average values of the total engine room space per kilowatt of rated capacity are seen to be as follows:—

TABLE LV.

Average Values for Engine Room Space per kw of Plant installed.

Type of Engine.	Engine Area in Sq m per Kw.	Total Engine Room Space in Sq m per Kw.	Space Factor in per cent.
(a) Horizontal Slow Speed	0,10	0,30	33 %
(b) Vertical Slow Speed	0,065	0,20	32 %
(c) Vertical High Speed	0,050	0,17	30 %
(d) Parsons Turbine	0,014	0,06	23 %
(e) Curtis Turbine	0,014	0,055	25 %
(f) Gas Engine	0,13	0,55	24 %
(g) Water Turbine	0,034	0,07	50 %

These figures are representative values, although they vary in individual cases according to the extent to which space is provided around the individual engines. In column 4 the ratio of the space covered by the engines to the total engine room area is given. This may be designated the "space factor." From these average values one is able to determine the preliminary dimensions required for the engine room for a given rated capacity and a given type of generating set. Similar data for the boiler plant of several of the stations of Table LIV. are given in Table LVI. In column 22 we have the boiler house area per kilowatt of rated capacity of the generators, and in column 25 the ratio of boiler house area to the engine room

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	8
	Total Capacity of all Boilers, Tons of Steam per Hour.
	108
	14,8
…,4	147
…,4	
…,8	
	50
	130
	86

area. It may be noted that the latter ratio increases as the rated speed of the generating plant in the engine room increases. Thus, for steam turbines, the boiler house occupies about 50 per cent. more space than is occupied by the engine room. The boiler house thus occupies some 60 per cent. of the total area. For piston engine stations the boiler house only occupies some eight-tenths as much space as is occupied by the engine room, or only some 45 per cent. of the total area. From these figures the preliminary dimensions for the boiler house may be determined for a given rated capacity of plant. Column 11 shows that the ratio of heating surface to grate surface averages about 50. From these data the following values may be deduced:—

TABLE LVII.

Average Values for Boiler House Design.

	Average Values.
(1) Heating surface per ton of steam evaporated per hour (normal rated capacity) . .	60 sq m
(2) Floor area per sq meter of heating surface .	0,075 sq m
(3) Floor area per ton of steam evaporated per hour (normal rated capacity) . . .	4,5 sq m

Preliminary Calculations for Generating Station Design.—Before proceeding further with the general principles of design of the other parts of the station, it is proposed, as an example, to make some preliminary calculations for a particular case. For this purpose let us take a generating station for an annual output of 270 million kw hr at a 50 per cent. load factor. This is the case which has already been considered in Chapter II., where it was shown that it was necessary to install 8 generating sets, each of 6800 kw rated capacity, and that the average coal consumption would be 33 tons per hour or a total of 290 000 tons per year.

Let us first consider the engine room. From Table LV. we see that the average engine room area required for steam turbine generating sets is 0,05 sq m per kw. Thus there are required $0{,}05 \times 55\,000 = 2750$ sq m of engine room space.

Before deciding on the proportions of the engine room, let us make a similar estimate for the boiler house.

The proportions of both engine room and boiler house, if not

restricted by the shape of the site, will depend only on the grouping of the plant. For a single 6800 kw generating set we found in Chapter III., p. 60, that 51 tons of steam per hr were required when operating at rated load. In Table LVII. of this chapter, 60 sq m was shown to be an average value for the boiler heating surface per ton of steam per hour. Hence for the 6800 kw set, $51 \times 60 = 3060$ sq m of boiler heating surface are required. Taking a large standard boiler of 750 sq m heating surface, it is seen that four boilers are required for each generating set. For the

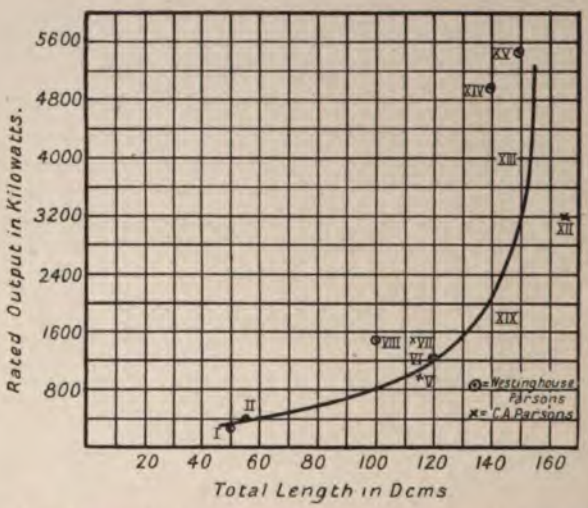


Fig. 73. The Overall Length of Parsons Turbo-generating Sets.

eight 6800 kw sets we must provide $8 \times 4 = 32$ boilers with a total heating surface of 24 000 sq m.

In order to obtain an estimate of the space required for boilers of this total heating surface, we may employ the figures obtained in Table LVII. of this chapter. From this table it is seen that the boiler space required amounts to 0,075 sq m per sq m of boiler heating surface. Hence in this case we require $0{,}075 \times 24\,000 = 1800$ sq m of space for the boilers, or 225 sq m for each set of four boilers.

The total area of boiler house floor may be obtained from this figure as also a value for the space factor of the boiler house. In well-designed boiler houses the space factor amounts to from 50 per

cent. to 60 per cent. Taking for our case a value of 55 per cent., 3300 sq m of boiler house floor area are found to be required. The ratio of boiler house area to engine room area is $\frac{3300}{2720} = 1{,}2$. Let us next consider the dimensions of the buildings. Three good alternatives which may be employed for a plant of this nature are the types outlined in Figs. 64, 67 and 68. In the case of Fig. 64 the double row of piston engines should be replaced by a single row of horizontal steam turbines.

We first require to know the dimensions of the 6800 kw turbine set.

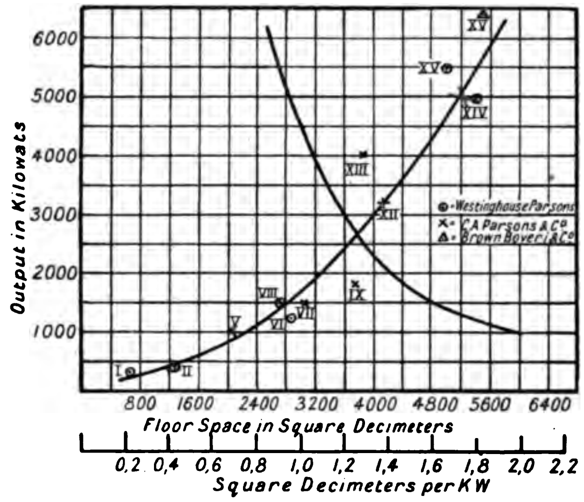


Fig. 74. FLOOR SPACE OCCUPIED BY PARSONS TURBO-GENERATING SETS.

Fig. 73 shows the overall length of Parsons turbo-generating sets. For a 6800 kw set, the overall length is about 16 m. The area occupied is found from Fig. 74 to be about 60 sq m, giving an overall width of about 4 m.

Alternative Arrangements of Generating Plant.—Each of the alternative arrangements comprises a double set of boilers. Thus the problem resolves itself into accommodating 4 units, each consisting of 8 boilers and 2 turbo-generators.

Figs. 75 and 76 are on the lines of Fig. 64
Fig. 77 is „ „ „ 68
and „ 78 „ „ „ „ 67.

Two other interesting designs for very large electricity stations

are shown in Figs. 79 and 80. Of these the arrangement in Fig. 77 is selected as being very suitable, since it provides the most direct path for the flow of energy through the station.

If the coal is delivered at the upper side of the boiler house and the switchboard is located along the lower side of the engine room, we have a straight path from the coal to the outgoing feeders from

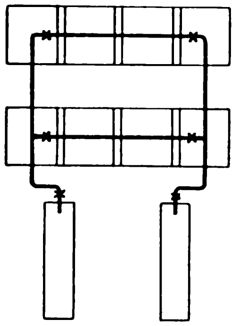


Fig. 75.

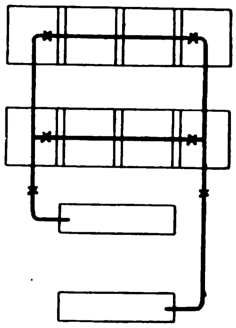


Fig. 76.

Fig. 77.

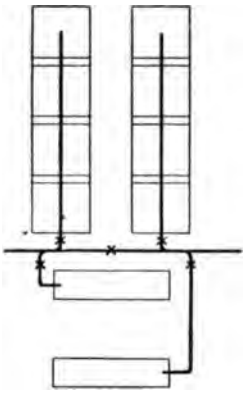


Fig. 78.

Figs. 75—78. Alternative Arrangements of Boilers and Turbo-generating Sets

the switchboard. The outline of the engine room and boiler house is indicated in Fig. 81.

The next matter for consideration is that of the flues and the chimneys. The most symmetrical arrangement for the case under consideration is that indicated in Fig. 81. Let us consider more in detail the general proportioning of chimneys and the related question of economiser proportions and of suitable provisions for coal storage.

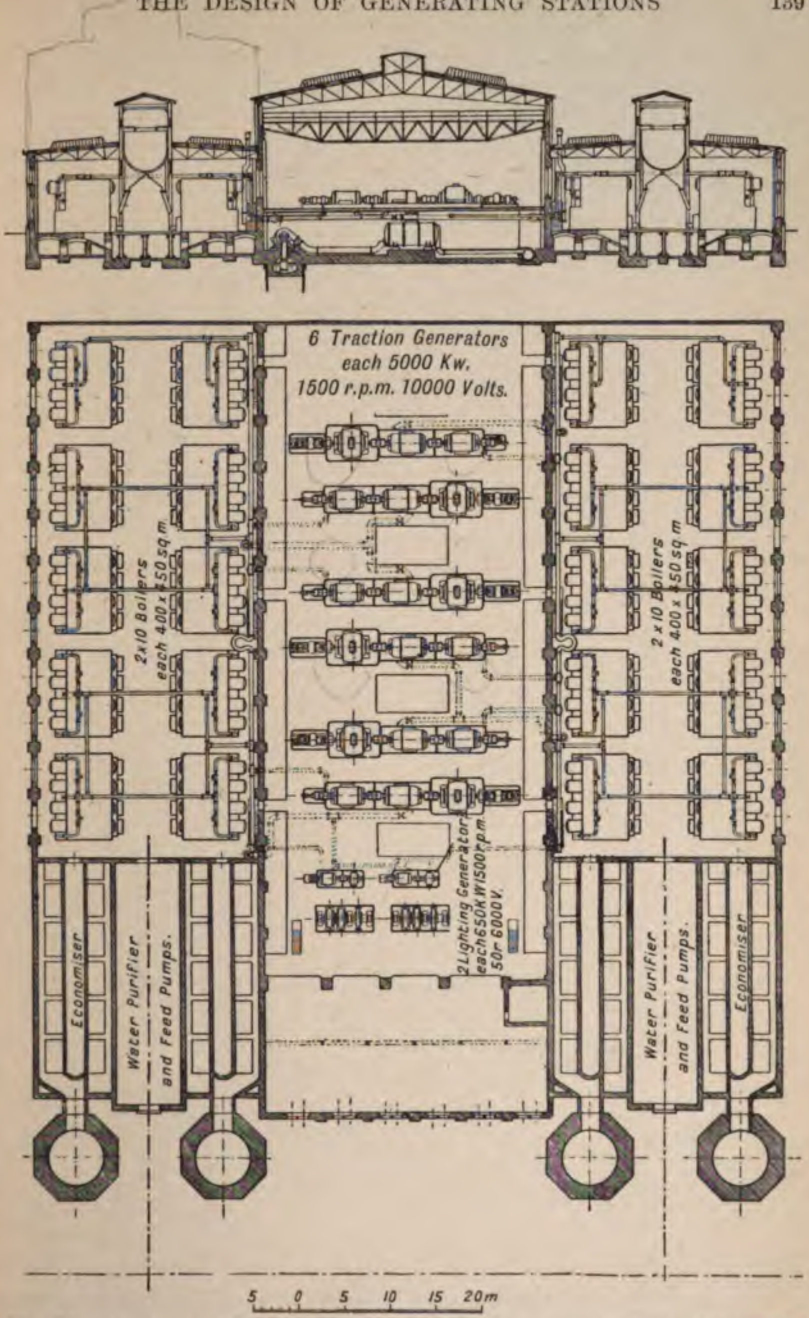


Fig. 79. Plan and Elevation of Power House proposed for supplying Electricity for Operating the Berlin Elevated Railways.

For the present we have shown, in Fig. 81, one economiser in the flue leading to each chimney.

Coal Storage.—It is desirable that provision should be made for

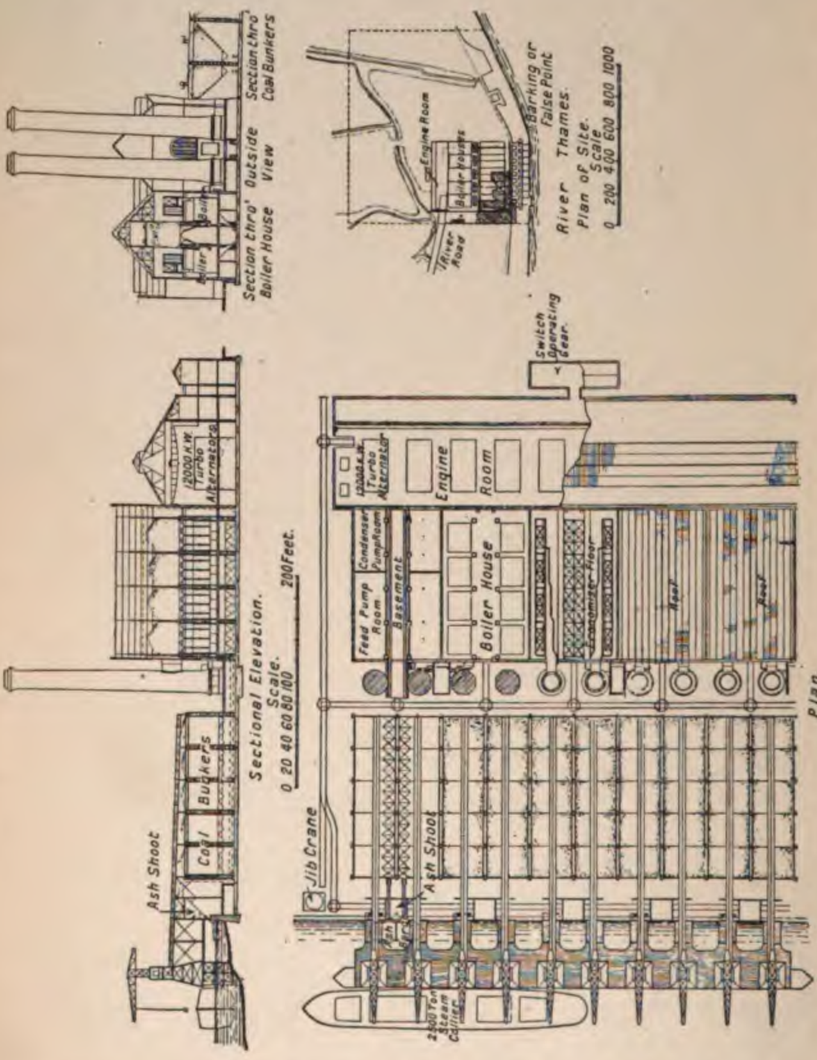


Fig. 80. London County Council Electricity Supply, 1907. General Arrangement of Proposed Generating Station at Barking.

storing a quantity of coal sufficient to last for a few weeks. This is drawn on in the event of the supply being cut off through interruptions of the railway or waterway services or from any other cause.

In Table LVIII. we have brought together data of the coal storage for the generating stations in Tables LIV. and LVI. The period for which the store suffices varies from one to three weeks. With a large station burning a large amount of coal per day, the space required for storing coal for a period of over a week becomes a serious consideration.

In estimating the provision for storage the average coal consump-

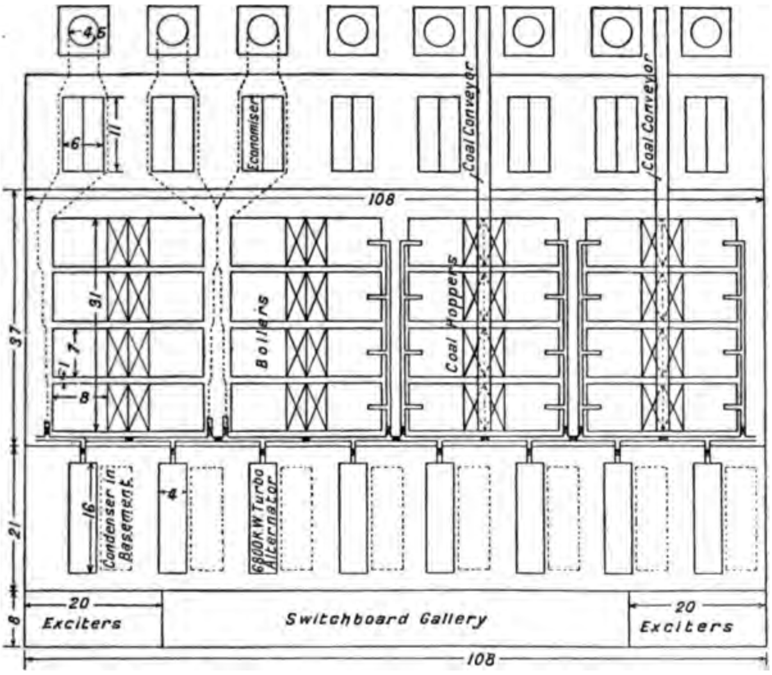


Fig. 81. PRELIMINARY OUTLINE OF GENERAL ARRANGEMENT OF 270 MILLION KW HR PER ANNUM GENERATING STATION.

tion should be used and allowance should be made for sufficient capacity for a couple of weeks' coal consumption. Another method of making a preliminary estimate is from the basis of the tons storage capacity per kilowatt of rated output of station plant. This figure has been included in Table LVIII. for the plants considered, and averages 0,2 ton.

For the 270 million kw hr per annum plant which we have been considering, the coal consumption amounts to 800 tons per day. Storage for one week would require a capacity of 5600 tons, or 0,1 ton

TABLE LVIII.

Particulars of Coal Storage for Generating Stations.

Reference No.	Name of Station.	Average Coal Consumption, Tons per Day.	Delivery of Coal.	Capacity of Coal Storage Bunkers, Tons.	Time for which Coal Store would last, Days.	Capacity of Coal Store per Kw of Plant installed, Tons.
1	Central London Railway	130	Rail	1000	14	0,14
2	Liverpool Southport Railway	110	Rail			
3	Bath Electric Tramways		Rail	50		0,075
4	Brussels Tramway Co.		Canal			
5	Charing Cross and City E.S. Co.		River			
6	Great Northern and City Railway	57	River	800	14	0,23
7	Manchester Corporation (Stuart St.)		Rail	1000		0,10
8	Salford Corporation		Canal	1600		0,25
9	Dublin Tramways (Ringsend)		River	2000		0,60
10	Glasgow Tramways		Rail	4000		0,35
11	Kelham Island P. Co., Sheffield					
12	Mersey Tunnel Railway		Rail			
13	Leicester Corporation Tramways		Canal			
14	Stalybridge Tramways					
15	Interboro R. T. Co., U.S.A.	970	River	18 000	18,5	0,28
16	Birmingham (Summer Lane)		Canal	2000		0,075
17	Central Electric Supply Co.		Rail	1200		0,065
18	West Ham Corporation			1600		0,28
19	Wolverhampton Corporation					
20	Wimbledon Electricity Works		Rail			
21	Hackney Electricity Works		River	500		0,10
22	Chelsea (Alpha Place)					
23	Birmingham Tramways (Smethwick)					
24	Ilford Electricity Works					
25	Greenock Electricity Works					
26	Lowestoft Electricity Works					
27	Poplar Electricity Works			300		0,19
28	Middlesborough Corporation					
29	Burnley Corporation					
30	Eastbourne Corporation		Rail			
31	Bournemouth Corporation			68		0,06
32	Christchurch Electricity Works			75		0,19
33	Bridlington Electricity Works					
34	Metropolitan District Ry., Lot's Road	800	Rail	15 000	21	0,26
35	Metropolitan District Ry., Neasden	182	Rail	1500	8	0,105
36	Newcastle E.S. Co., Carville	157	Rail	1200	8	0,11
37	Clyde Valley E.P. Co., Yoker		Rail			
38	Sheffield Corporation, Neepsend		Rail	1000		0,17
39	North Met. E.P. & S. Co., Brimsdown		River	1000		0,23
40	Long Island City, Penn., U.S.A.			5200		0,16
41	Frome Electricity Works			60		0,21
42	Brighton Corporation		Water	4000		0,24
43	Yorkshire E.P. Co., Thornhill		Rail			
44	Lancashire E.P. Co., Radcliffe		Rail			
45	Quincy Point, Mass., U.S.A.		River			
46	Walthamstow Corporation	43	Rail			
47	Leek Electricity Works					
48	North Wales P. & T. Co., Snowden					

per rated kw installed. One ton of coal, allowing for the space between the lumps, occupies about 1,2 cu m. Thus the cubical capacity of the coal store will be 1,2 × 5600 = 6700 cu m. The coal store should be placed at that end of the boiler house at which the coal is delivered, so that the coal may be fed directly into the conveyor which takes it up to the hoppers above the boilers.

Chimneys.—Let us now briefly consider the means for bringing to the grate the requisite supply of air, and of propelling the furnace gases over the surfaces to be heated, and of ultimately removing the waste products. Notwithstanding the advantages of induced and

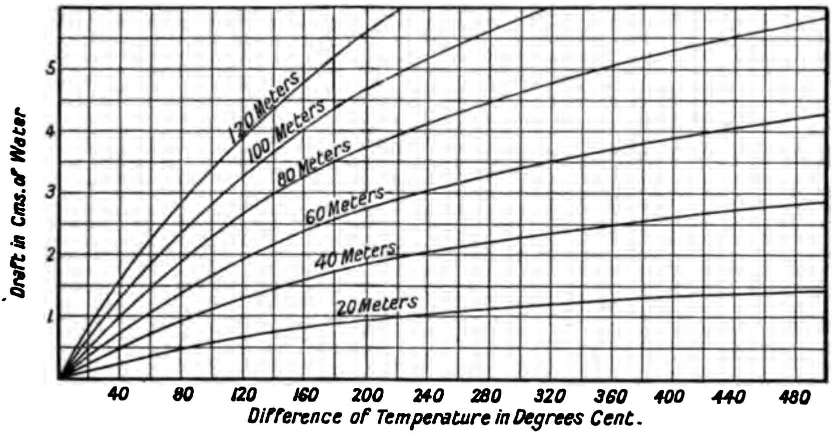


Fig. 82. CURVES SHOWING THE DRAUGHT OBTAINED FROM VARIOUS CHIMNEYS WHEN THE TEMPERATURE AND THE HEIGHT OF THE SHAFT ARE VARIED.

forced draught systems, the general preference is still for natural draught in spite of the considerable cost of chimneys.

With a view to the more effective removal of the gases, chimneys are often built much higher, and consequently on more expensive lines, than are required for the provision of the necessary draught. A height of 150 m is, however, rarely exceeded.

In Table LIX. are given particulars of the chimneys of a number of electric generating stations. There is excellent agreement with respect to the weight of furnace gases carried away per hour per square decimeter of sectional area of chimney.

The draught produced by a chimney, and the volume of gas flowing through it per hour per unit of sectional area, depend upon the difference in the absolute temperature between the gases inside the

TABLE LIX.

Particulars of some Typical Chimney Shafts.

	Number of Shafts.	Material.	Height in Meters.	Internal Diameter in Meters.	Area of Shaft in Sq Dms.	Number of Boilers per Shaft.	Tons of Coal per Shaft.		Weight of Gas in Tons per Hour for Ratio of 20:1.		Rate, in Kw of expenditure of energy of Coal.		Volume of Gas, Cu M per Sq Dm of Shaft per Hour.	Speed of Gas in Meters per Sec.
							Total per Year for 50 per cent. Load Factor.	Maximum per Hour.	per Shaft.	per Sq Dm of Shaft.	per Shaft.	per Sq Dm of Shaft.		
A	B	C	D	E	F	G	H	J	K	L	M	N	O	P
Chelsea (Lots Rd.)	4	Brick	90,3	5,8	2630	16	68 500	14,6	305	0,116	126 000	48	145	4,0
Glasgow . .	1	,,	82	4,88	1870	16	53 600	12,26	257	0,137	107 000	57	173	4,8
I.R.T., N.Y. .	6	,,	74	4,57	1640	12	59 600	13,5	285	0,174	151 000	92	220	6,1
Neasden . .	1	,,	65,5	4,57	1640	10	66 500	15,2	320	0,195	170 000	104	246	6,8
Greenwich . .	2	,,	86,3	4,27	1430	12	27 000	7,6	160	0,112	97 500	68	141	3,9
C.L.R. . . .	2	,,	82	3,05	730	8	12 600	2,9	61	0,084	73 000	100	106	2,95
Brimsdown . .	1	Steel	52,5	3,04	725	6	20 000	4,6	96	0,132	115 000	159	166	4,6

chimney, and the air outside. For chimneys of from 20 to 120 m in height, the values are worked out in the curves of Fig. 82.

For the plants studied in Table LIX. the precise conditions as regards temperatures have not been analysed. The temperature of the gases on entering the chimney has been assumed as 175° C in all these cases. At this temperature, a ton of the furnace gases

TABLE LX.

Relation between Weight and Volume of Air at different Temperatures.

Temperature.		Relative Volume.	Weight Kg per Cu M.	Volume Cu M per Ton.
Centigrade.	Absolute.			
—10	263	0,96	1,36	735
0	273	1,0	1,3	770
10	283	1,04	1,25	800
20	293	1,07	1,2	825
30	303	1,11	1,17	855
40	313	1,15	1,13	885
50	323	1,18	1,1	910
60	333	1,22	1,07	940
80	353	1,29	1,01	990
100	303	1,37	0,95	1060
120	393	1,44	0,91	1110
140	413	1,51	0,86	1160
160	433	1,59	0,82	1230
180	453	1,66	0,78	1280
200	473	1,73	0,75	1330
250	523	1,92	0,61	1480
300	573	2,1	0,62	1620
350	623	2,28	0,57	1750
400	673	2,47	0,53	1900
450	723	2,65	0,49	2040
500	773	2,83	0,46	2180

occupies a volume of 1260 cu m, as against a volume of 850 cu m at 25° C, the ordinary temperature of the atmosphere. These values are taken from Table LX. Thus a cubic meter of furnace gas in the two cases weighs:

At 25 degs. Cent. . . 1,18 kg.
„ 175 „ „ . . 0,79 „

For every meter height of chimney, there is a difference of pressure of 1,18 – 0,79 = 0,39 kg per sq m, or 0,039 g per sq cm.

A chimney with a height of 100 m thus produces a draught equal to 3,9 g per sq cm.

Since 1 sq cm of water weighs one gram, this 100-meter chimney produces a draught equal to the pressure of a column of water of a height of 3,9 cm *i.e.*, the draught in cm height of water column is equal to 3,9.

For other temperatures of the furnace gases when entering the chimney, the suitable values of the density of these gases may be taken from Table LX.

For coal of a calorific value of 8700 kw hr per ton, 20 tons of air should be supplied per ton of coal burned; *i.e.*, 1 ton of air should be supplied for every $\frac{8700}{20} = 435$ kw hr of calorific value of the coal burned. Allowing for loss in ashes and in radiation from furnace, we may say that the calorific value of one ton of furnace gas at 1300° C is about 400 kw hr, or, say, about 0,31 kw hr per deg. Cent. Thus for a generating station with 10 per cent. overall efficiency, 1 ton of air should be supplied for every 43,5 kw hr output from the station.

The theoretical quantity is only 12 tons of air per ton of coal, but in practice the weight of air is seldom reduced below 16 tons per ton of coal burned, when this coal has a calorific value of 8700 kw hr per ton; 20 tons of air per ton of coal burned is a good representative figure.

It is desirable to proportion the chimney with sufficient draught to permit of operating the boilers for a short time at 50 per cent. or more above their rated capacity.

For the 270 million kw hr station regarding which we have calculated the boiler plant, eight chimneys should be installed; each serving four of the thirty-two boilers. Each of these boilers is rated at 9600 kw, or

$$4 \times 9600 = 38\ 400 \text{ kw}$$

for the four boilers served by one chimney. At a 50 per cent. overload, we have

$$1,5 \times 38\ 400 = 57\ 600 \text{ kw}$$

If we take a boiler efficiency of 70 per cent. at this overload, we must burn coal at the rate of

$$\frac{57\ 600}{0,70} = 82\ 000 \text{ kw}$$

or

$$\frac{82\ 000}{8700} = 9,4 \text{ tons per hr.}$$

Thus we should require $20 \times 9{,}4 = 190$ tons of air per hr. It is not desirable to estimate on transmitting more than 14 tons of furnace gases per sq m per hr, at the maximum overload. Hence we require $\frac{190}{14} = 13{,}6$ sq m section per chimney, or a diameter of 4,2 m per chimney, or say 4,5 m.

Estimating on a temperature of 175° for the gases entering the chimney, we have a volume of 1260 cu m per ton. The gas must be transmitted at the rate of

$$\frac{190}{3600} = 0{,}053 \text{ ton per sec, or}$$

$$0{,}053 \times 1260 = 67 \text{ cu m per sec.}$$

As the section is 13,6 sq m the velocity must be

$$\frac{67}{13{,}6} = 4{,}9 \text{ m per sec.}$$

Let the chimney have a height of 100 m. We have seen that the "draught" in a 100-m chimney amounts to 3,9 g per sq cm. The total pressure is thus

$$\frac{13{,}6 \times 10\,000 \times 3{,}9}{1000} = 530 \text{ kgs.}$$

Thus work is being done at the rate of

$$530 \times 4{,}9 = 2600 \text{ kg m per sec.}$$

$$1 \text{ kg m per sec} = 9{,}81 \text{ w.}$$

Work is, consequently, being done at the rate of

$$\frac{9{,}81 \times 2600}{1000} = 26 \text{ kw.}$$

This is of some interest in getting an idea of the general order of magnitude of the power which would be required in driving fans where induced or forced draught systems are employed. A large multiplier should be employed in connection with the above figure, and this should vary with the varying conditions of each case.

This 26 kw is almost entirely required to overcome the friction of the air through the grate and the fuel, then on amongst the boiler tubes, superheater tubes, and economiser tubes, and afterwards through the chimney.

Forced draught systems have the disadvantage of increasing leakage of the air and gases. Induced draught systems avoid this objection, but have the disadvantage that the fan works in a medium of such high temperature and composition as to be subject to rapid deterioration.

Economisers.—If, after passing through the boiler, the gases are

carried through an economiser, the temperature of the gases will be lowered by an amount proportional to the extent of economiser tube surface installed. The gases may thereby be reduced to so low a temperature that it would not be practicable to obtain the necessary draught entirely by a chimney, and the chimney must be supplemented by an induced draught installation. When the temperature of the gases on emerging from the economiser to pass to the chimney is much less than 150° Cent. it is generally impracticable to obtain the required draught by the chimney alone.

Thus there arise a number of conflicting considerations with regard to the extent of economiser surface which can be economically installed, and even whether it should not be altogether dispensed

TABLE LXI.

Data of Economisers.

No.	Name.	No. of Economisers.	Total No. of Tubes.	Total Economiser Heating Surface (Sq M).	Area of Floor.	Ratio of Heating Surface to Floor Area.	No. of Boilers.	Total Boiler Heating Surface.	Ratio of Boiler Heating Surface to Economiser Heating Surface.
	Central London Railway .	2	1536	1570	160	10,0	20	6640	4,3
	Liverpool Southport Railway	2	1440	1350	104	13,0	16		
	Met. Dist. Railway, Neasden	1	1760	1700	73	23,0	8	4240	2,5
	Clyde Valley, Yoker . .	3	1920	2000	136	14,7	14	5700	2,85

with. The use of considerable economiser surface involves not only the outlay to cover its own cost, but may also involve further outlay for an artificial draught installation. In general it may be said that economisers and artificial draught should only be installed where the price of fuel is very high. Of course the most economical proportion is obtained when the sum of the operating costs and the capital costs is a minimum.

Space occupied by Economisers.—In determining the space which should be allowed for the economiser in laying out the general design it is desirable to have an idea of the relation between the heating surface and the floor area occupied by the economiser.

Published data as to precise details of economiser plant is scarce, but Table LXI. gives data for the economisers of four typical generating stations.

From these we may take an average value of the ratio of heating surface to floor area as 15.

For purposes of obtaining a rough idea of the space to be allowed for the economisers with a view to completing the preliminary lay-out drawing of Fig. 81 we may take the total economiser heating surface as one-third of the total boiler heating surface.

For the 270 million kw hr plant considered, we have 3300 sq m of boiler heating surface for each group of 4 boilers, and we shall allow 1000 sq m of economiser surface for each group. We have 8 chimneys, and shall thus have one economiser in the flue leading to each chimney.

The floor area required per economiser is $\frac{1000}{15} = 66$ sq m. The maximum width which we can allow for the economiser is ascertained from the drawing in Fig. 81 to be 6 m.

Hence the length of the area occupied is $\frac{66}{6} = 11$ m. These areas are indicated in the flues in Fig. 81, and beyond them are the chimneys of 4,5 m diameter.

Steam Piping.—For the main steam range, practice tends towards a straight main to which all the boilers are piped and from which the engines may be supplied. Where there is a large number of boilers, as in the case we are considering, they may be split up into several batteries, each with its own main. The main range is subdivided into sections for each group of boilers, with valves which enable any group to be cut out from the steam supply.

When the plant is laid out on the "unit" system (as in Fig. 81 for the case we are considering) some engineers have gone so far as to isolate each of the groups of boilers, so that it can only feed one generating set. This plan has the disadvantage that should one of the engine sets break down its set of boilers is rendered idle.

Let us first briefly outline the general scheme of piping and afterwards go further into the detail arrangements.

Fig. 83 is a skeleton drawing which shows the piping necessary for one unit of the plant. This diagram is arranged on similar lines to those customary in a diagram of electrical connections. There are two main circuits, the steam circuit and the condensing water circuit.

Main Steam Circuit.—In the main steam circuit the steam is raised in the boilers and passes on to the engines. After doing its work in the engines the exhaust steam goes to the atmosphere if non-condensing, and otherwise to the condenser. When exhausting to the atmosphere the exhaust steam is often taken up the chimney shaft. In the condenser the steam is condensed and passed on to

the hot well; from the hot well it is pumped back as feed water into the boilers, thus completing the circuit. On its way from the hot well to the boiler the feed water passes through the economiser situated in the main flue before the chimney. The economiser

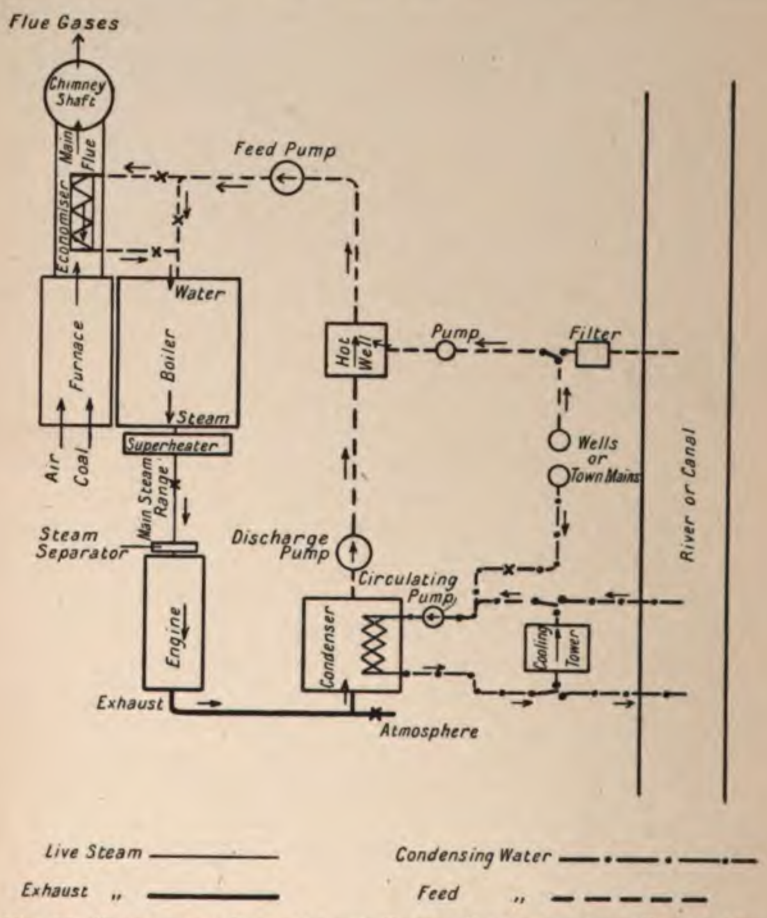


Fig. 83. Connection Diagram for Steam Plant showing Steam and Water Circuits.

may be short circuited when required to be shut down. To make up the deficit in feed water caused by leakage of the steam at pipe joints and other points, the hot well is provided, as shown, with a delivery of extra feed water drawn from the source of supply of feed water. This may be a river, a canal, a well or the town mains.

Condensing Water Circuit.—In the diagram, two parallel circuits are shown for the condensing water. The first shows the cooling water drawn from the canal or river by the circulating pump and returned thereto after passing through the condenser where it condenses the steam. As an alternative to this, the same water may be used repeatedly by cooling it after leaving the condenser, in cooling towers or in a cooling pond.

The diagram Fig. 83 illustrates all the piping necessary for a condensing station with economisers. In the design of the piping system the principal problem is to reduce the lengths of all piping, and the complication, to a minimum. The chief factor in this is the arrangement of the various pieces of apparatus relative to one another. Thus the engines are placed as near to the boilers as possible and the condensers near the engines. In the case of small plants, a central condensing plant is used and is best, but with large plants with units each of several thousands of kilowatts rating, the practice is to provide each engine set with its own condenser. In this case the condenser is located either beside the engine or below the engine on a lower floor.

In Fig. 81 the principal piping connections for the 270 million kw hr per annum station have been drawn out. The scheme follows that of Fig. 83, but the apparatus is grouped in the way in which it is actually laid out.

Details of Piping.—In laying out the piping system, apart from the main scheme, care should be given to several details, among which are drainage, expansion and vibration. Nowadays the main steam piping system is not duplicated, but it is more usual to duplicate the feed water piping system in view of facility for overhaul. Drainage is important in exhaust pipes when running non-condensing, as water may drain back in to the engines from the exhaust. For draining the live steam system the main range should be situated below the level of the boiler stop valves as in Fig. 84, so that any water which collects drains away from the boilers and may be drawn off at a few well-marked points.

Against expansion, large bends are provided, and these should be more numerous the greater the lengths of steam piping.[1]

[1] R. McGregor, in a series of articles entitled "Steam and Exhaust Pipes" (*Electrical Times*, 1907, pp. 284—886), gives a number of types of expansion bend and many other details. *Electrical Engineering* for December 19, 1907, contains, at p. 973, an excellent article entitled "Steam Pipe Systems for Generating Stations," by J. H. Rider, M.Inst.C.E.

The velocity of steam in steam pipes varies between 16 and 34 m per sec, the higher values obtaining with superheated steam. Still higher values may be used if the engines are far from the boilers, in order to economise on initial outlay for pipework.

For the station we have been designing, the maximum steam consumption amounts to 408 tons per hr for the maximum load of 54 400 kw. The volume of steam taken from the boilers per hr is 60 000 cu m taking steam at a specific gravity of 6,8, or 16·7 cu m per sec. Taking a steam velocity of 25 m per sec we require a cross-section of 67 sq dm to carry all the steam. Were we to allow a main steam range sufficient to carry this entire quantity of

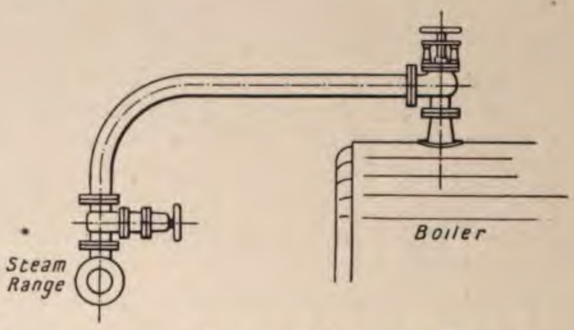


Fig. 84. Showing Correct Location of Main Range.

steam, the diameter would be 92[1] cms. The main range is, however, never called upon to carry the total amount of steam owing to the grouping of the boilers shown in Fig. 81.

The branch pipes from the boilers require sufficient section to carry the steam generated by each boiler. Each boiler supplies a maximum of 12,5 tons of steam per hr, and the section required is thus 210 sq cm, or a diameter of 16,4 cms.

The branch pipes to each of the engines have to deal with 51 tons per hr, and require to be of 840 sq cms area or 32,8 cms diameter. The principal piping is shown in Fig. 81. The circuits are similar to the skeleton diagram of Fig. 83.

Fig. 85[2] shows a typical arrangement of steam piping.

Exciters.—It is distinctly preferable to have separate exciter sets

[1] On the basis of 0,2 sq dm per ton of steam per hr (see Chap. III. p. 68), we get 408 × 0,2 = 82 sq dm, or a pipe of 102 cm diameter.

[2] Reproduced by permission from the *Electrical Times*, p. 763, vol. 31 (R. McGregor, "Steam and Exhaust Pipes").

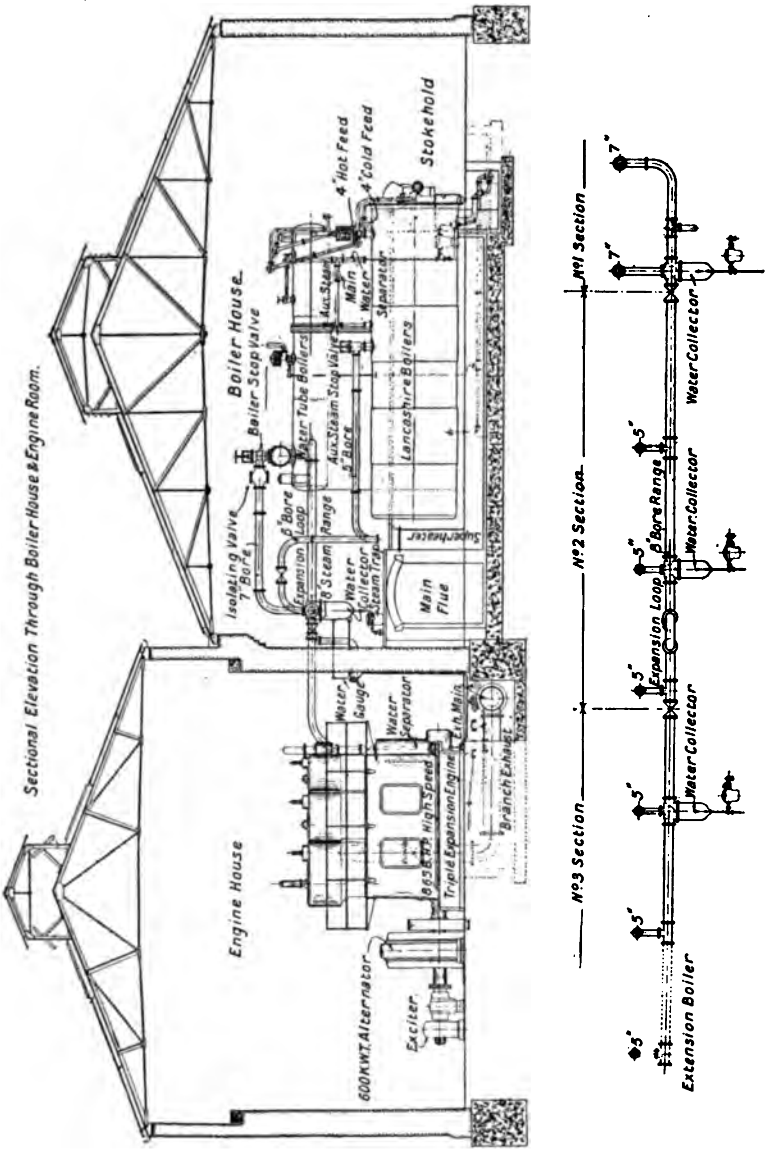


Fig. 83. Typical Arrangement of Steam Piping.

rather than to employ exciters directly connected to the main generator shafts. Separate exciter systems have several advantages over direct-connected exciters. They permit of greater flexibility, as any one exciter is not confined to use with one particular generator. A breakdown in a direct-coupled exciter puts the main set out of operation. Separate exciters permit of better voltage regulation, since with a direct connected exciter any drop in speed in the engine drops the voltage of the exciter and the alternator excitation. The drop in voltage in the alternator is thus cumulative by reason of the drop in speed and the drop in excitation. This consideration is not of such moment with turbine generators as the speed regulation is very close. Vertical high-speed engines direct-coupled to continuous current generators are the standard type of exciter.

TABLE LXII.

Excitation Power required for Alternators.

Rated Output Kw.	Power required for Excitation at Full Load.							
	High Speed.				Slow Speed.			
	P.F. = 1.		P.F. = 0,8.		P.F. = 1.		P.F. = 0,8.	
	Kw.	Per cent.	Kw.	Per cent.	Kw.	Per cent.	Kw.	Per cent.
500	2	0,4	3	0,6	5	1,0	7	1,4
1000	5	0,5	7	0,7	7	0,7	10	1,0
2000	9	0,45	13	0,65	11	0,55	15	0,75
4000	13	0,33	18	0,45	16	0,4	22	0,55
8000	16	0,2	22	0,28				

Data for the space occupied by such plant will be found in Table LIV., from which we may derive the average value of 0,1 sq m per kw for the actual space occupied by the sets.

From this table we may also obtain the average proportion of the total engine room space allowed for the exciters. This averages 7,5 per cent. of the total engine room area. In the 270 million kw hr plant the engine room area is 1800 sq m, and we have allowed 144 sq m for the exciter space. In Fig. 81 we have extended the engine room on one long side to allow for the switchboard and exciters. The switchboard thus placed allows of the simplest and shortest path for the cables for the main generators and for the exciters. In estimating the capacity of the exciter plant we must install sufficient plant to supply power to as many of the main

generators as are required to deal with the maximum load, and an allowance for stand-by.

In Table LXII. are given the average values of the excitation power required for polyphase slow-speed and turbo-alternators from 500 to 8000 kw rated output.

For our 6800 kw unit the maximum excitation at 0,8 p f and full load will be about 20 kw.

The maximum load on the station amounts to 54 000 kw for the 8 main generators. The total exciting power is thus 160 kw.

Allowing 50 per cent. stand-by, we should install exciters amounting to 240 kw. These will best be arranged as 4 sets placed as shown in Fig. 81.

Auxiliary Plant.—When estimating the exciter continuous current

TABLE LXIII.

Costs of Generating Stations.

	£ per kw.
Buildings and chimneys . . .	1,5 to 2
Coal handling plant	1,5
Boilers	1 to 3
Superheaters	0,25
Economisers	0,5
Steam piping and valves . . .	0,5
Reciprocating engines and generators	6 to 10
Turbo-generators	3 to 6
Condensers	0,5
Switchgear	0,2

plant, there arises the question of the driving of the auxiliary station apparatus and the station lighting. If the auxiliaries are to be driven by continuous current motors sufficient continuous current plant must be installed to deal with this load and that due to the main excitation. Running the auxiliaries by continuous current from separate sets renders them quite independent of the main generator sets. If the auxiliaries are driven with alternating current from the main generators, a complete breakdown in the latter, if few in number, will shut down all the auxiliaries, including the boiler feed pumps, if so driven.

The driving of the auxiliaries is in this case dependent on the running of two sets of machines—the exciters and the main

generators, while if run from the exciter sets only, the risk of breakdown is halved. In this connection, steam-driven accessories have the advantage that they are only dependent on the boilers for operation, and are independent of faults which may occur in the steam piping, engines, generators, exciters, or switchboards.

Costs.—In Table LXIII. are given the average costs per kw for the various components of a large generating station for an annual output of over 100 million kw hr per year.

The complete cost of a station well designed on modern lines for an output of over 100 million kw hr per year need not exceed £10 per kw.

CHAPTER VIII[1]

Section 1.—High-tension Power Transmission Lines

Up to the outgoing mains from the generating stations neither the capital costs nor the generating costs are appreciably different whether the electrical energy is supplied in the form of continuous current or of polyphase alternating current, nor will the voltage of the supply affect the result to any considerable extent. The cost of the transmission system, however, is a function of the form of electrical energy, and of the voltage at which it is supplied. To transmit a given amount of power (at a given voltage between conductors and at a given loss in transmission) the three-phase system requires the least section of copper, and will consequently be the most economical system.

The copper conductors may be supported overhead on poles or towers, in which case they are usually left bare; or they may be insulated and laid underground, in which case three-core lead covered cable is used.

In this chapter we shall estimate the complete costs of overhead and underground transmission lines for various amounts of power transmitted and for various voltages between conductors. Then, from the results obtained in these particular cases, we shall, by curve plotting processes, deduce certain general conclusions as to the cost of any transmission line. In order to make these results quite general we shall express the costs as a function of the section of the conductor.

For both overhead and underground transmission at a given pressure, the cost per kilometer per kilowatt transmitted decreases with increasing amounts of power transmitted per line, so that it is cheaper to transmit over one heavy line than over several small lines. This is, however, rarely a practical plan, and in the interests of a reliable and continuous supply, the line must be split up into two or more circuits operating in parallel. In the event of one circuit breaking down, the whole load, or nearly the whole load, can be supplied by overloading the other circuit or circuits.

[1] Since writing this chapter the prices of copper and aluminium have undergone such great changes that the reader must modify the results in the chapter to accord with the latest market prices of these metals.

There is also a limit to the section of copper that can be conveniently handled. This limit may be taken as about 300 sq mm per core for a three-core cable, and 200 sq mm for an overhead conductor. Of course, there may at any time occur developments leading to the successful use of larger conductors, both overhead and underground, but at present the above values constitute reasonable limits.

From the curves deduced in the following investigation, the increase in the cost of the transmission line, due to this dividing up of the line, may readily be obtained.

Voltage of Transmission.—Given a certain amount of power to be transmitted to a certain distance, we must first decide on the voltage of transmission. With regard to underground transmission by cables, it will be seen from the curves in Fig. 100 (p. 191) (which have been derived by the methods set forth in this chapter), that for any set of conditions there is a most economical voltage at which the cost of the cable will be a minimum.

With overhead transmission, as will be seen from Fig. 92, this is not the case; the cost continues to decrease with increasing voltage, and, so far as the transmission line is concerned, it is an advantage to employ the highest practicable voltage, though the decrease in cost with increasing voltage is very slight after a pressure of 60 000 volts is reached. At higher voltages, however, the loss by brush discharge will be very considerable, unless conductors of large diameter are used and are placed at a considerable distance from one another. There is insufficient actual working experience with pressures greater than 70 000 volts to justify definite statements regarding the practicability of such pressures.

For short lines the most economical voltage will in both cases be 15 000 volts or lower, as with this or any lower pressure it will be unnecessary to use step-up transformers, and the electrical energy will be generated at this voltage. For long lines, however, the transmission voltage will range from 15 000 to 40 000 volts for a cable line, and from 20 000 to 80 000 volts for an overhead line, and in these cases step-up transformers are employed. With due regard to the above considerations and to Kelvin's Law,[1] which, applied to the present question, is to the effect that maximum economy is obtained when the annual cost at the generating station of the power wasted in transmission is equal to the interest, depreciation and maintenance of the transmission line, we can decide on the

[1] See p. 199 and Fig. 103A.

most economical voltage and section of copper conductor for any given scheme.

Frequency.—The next point to decide is the frequency of the alternating current.

Generally a very low frequency is desirable for transmitting any considerable amount of power over long distances. In so far as the transmission line is concerned, the lower the frequency the better, since the inductive drop on load and the capacity or charging current at no load are both directly proportional to the frequency. However, when synchronous motors form part of the load, the inductive drop on load, and also the capacity current on light load, can be neutralised. Synchronous motors are occasionally installed solely for that purpose. It is possible in this manner to bring the Power Factor up to unity and thus improve the regulation and efficiency of the line. As a matter of fact, however, this plan is rarely adopted.

The above considerations hold for both overhead and underground transmission. We will now proceed to treat each of the two cases separately, starting with overhead transmission.

Section 2.—Overhead Lines.

The cheapest method of transmission, when conditions permit of its use, is generally that in which uninsulated conductors are supported overhead. An overhead line is invariably used in cases of transmission over long distances through wild or sparsely populated districts. With a suitable line construction this method may also be employed with success in populated districts.

The line construction may consist either of wooden poles spaced 20 to 50 m apart, *i.e.*, 50 to 20 poles per km, or of steel poles with which the span may be from 40 to 100 m. Wooden poles are usually of cedar or of pine impregnated with a suitable preservative, and they cost from £2 to £4 each. Steel poles are more durable and are fireproof. They cost from £6 to £10 per pole. According to Kolkin[1] such a line may prove cheaper than a wooden pole line, as the cost of maintenance is so much less in the former case. For transmitting large amounts of power at high pressures, the *steel tower* construction is coming into general use, and will certainly be most generally employed in future transmission lines. We shall consequently assume a steel tower construction in the following investigation.

With steel towers the standard span may be anything between

[1] See *Electrical Review*, Dec. 28th, 1906.

100 and 200 m, and in extreme cases, as when crossing a river, may be as much as 400 or 500 m. A steel tower construction readily admits of structures of a size and strength impracticable with wood, and has also the advantage of being fireproof and more durable.

Steel towers for normal spans of about 150 m cost from £12 to £40 each. All the above costs are exclusive of the cost of pins, insulators and erection. Table LXIV. gives the average costs, spans and number of poles per km for the different constructions.

TABLE LXIV.

Costs of Poles and Towers.

Type of Construction.	Average Cost of one Pole or Tower exclusive of Pins and Insulators.	Average Span in Meters.	Corresponding No. of Poles or Towers per Km.	Cost per Kilometer.
Wooden pole line	£3	33	30	£90
Steel pole line .	£8	70	14	£112
Steel tower line .	£25	140	7	£175

The size, weight and cost of pole or tower will depend upon the pull exerted by the conductors, the distance they are to be placed apart, and the span from pole to pole. Let us first consider the conductor.

The Conductor.—Copper, aluminium or steel may each, under certain circumstances, be appropriately employed for the conductor. In most cases only copper and aluminium need be considered, but in extreme cases of very long spans and low frequency a steel conductor may be suitable. Having estimated the suitable section of conductor with reference only to the ohmic loss, it is necessary to see that this section shall give the required mechanical strength, and a radius of curvature large enough to prevent appreciable loss by brush discharge.

The stress in the suspended conductor is due to the weight of the conductor itself and to the wind pressure. The effect of snow or ice on the conductor need not be considered in this country, and even in most severe climates it is found that this extra load is only very remotely liable to occur at the same time as the maximum wind pressure.

No copper conductor with a section of less than 25 sq mm should be used, and no aluminium conductor of less than 50 sq mm. In all cases it is preferable to use a stranded conductor rather than a solid

conductor, since a stranded conductor is more elastic and flexible. Let us take the value of 10 kg per sq mm as the maximum permissible tensile stress in the conductor, this occurring when the lowest temperature (taken as — 25° C) and the maximum wind pressure (125 kg per sq m) occur together. This will give a good factor of safety under normal conditions, as these two extremes will rarely occur together, and a stress of 10 kg per sq mm is rather lower than one-half of the elastic limit and one-fourth of the breaking stress for good hard-drawn copper wire.[1]

This is a very conservative value for the maximum permissible stress. In America twice this value is often allowed, *i.e.*, about 20 kg per sq mm. The effect on the following calculations, of taking 20 instead of 10 kg per sq mm would be to halve the sag of the wires and thus reduce the necessary height of tower; but the pull of the wires at the top of the tower would be doubled, and the cost of the tower would generally be at least as great, if not greater.

Aluminium does not compare favourably with copper as regards most mechanical properties. It has less than one-half of the tensile strength of copper. It corrodes just as easily as copper, and is even more affected by salt sea fogs. For a given current-carrying capacity, the section of aluminium will be nearly 1,65 times the section of copper. As a consequence, the radius of curvature will be larger, which is an advantage at high voltages, since the tendency to brush discharge is less, the greater the radius of curvature.

For the following investigation, let us consider copper conductors having the sections shown in Table LXV.

TABLE LXV.

Data constituting Basis of Transmission Line Investigation.

Three-phase Duplicate Circuit Transmission Line. Three Conductors per Circuit. Six Conductors per Tower.					
Volts between Conductors.	Real Cross-section per Conductor in Sq Mm.				
10 000	25	50	100	150	200
20 000	25	50	100	150	200
40 000	—	50	100	150	—
60 000	—	50	100	150	—
80 000	—	50	100	150	—

[1] See also the recommendations of the "Sicherheits-Kommission" of the "Verband Deutscher Elektrotechniker," *Elektrotechnische Zeitschrift*, p. 545, May 23, 1907.

It is not considered safe to use a copper conductor of less than 25 sq mm section on a span of 143 mm, and 200 sq mm is the largest section that can be conveniently handled. At 40 000 volts, a 25 sq mm conductor, owing to its small diameter, occasions too great a leakage by brush discharge, and such a large amount of power as could be transmitted through a 200 sq mm conductor at 40 000 volts would not be transmitted through one circuit.

Consequently at 40 000, 60 000, and 80 000 volts examples are

TABLE LXVI.

Temperature Rise of Bright Copper and Aluminium Conductors in Still Air at 20° C.

	Diameter in Millimeters.	Cross Sectional Area in Sq Mm.	Copper. Degrees Centigrade Rise.						Aluminium. Degrees Centigrade Rise.					
			5	10	20	40	80	Fusing Point 1054	5	10	20	40	80	Fusing Point 655
Current Density in Amps per Sq Mm.	2	3,14	2,6	4,8	6,7	9,5	13,4	71,7	1,9	3,6	5,1	7,2	10,0	53,0
	4	12,6	1,8	2,8	3,8	5,6	8,1	50,8	1,35	2,1	2,85	4,2	6,0	38,0
	6	28,3	1,41	2,2	3,0	4,4	6,2	41,5	1,06	1,6	2,3	3,3	4,6	31,0
	8	50,3	1,27	1,8	2,5	3,6	4,9	36,0	0,95	1,33	1,87	2,7	3,7	27,0
	10	78,7	1,08	1,52	2,2	3,0	4,2	32,2	0,80	1,14	1,60	2,2	3,1	24,0
	12	113,2	0,95	1,32	1,87	2,6	3,7	28,4	0,70	1,0	1,39	1,96	2,7	22,0
	14	154,0	0,86	1,20	1,69	2,4	3,3	27,0	0,65	0,89	1,27	1,75	2,5	20,0
	16	201,0	0,78	1,10	1,54	2,1	3,1	25,5	0,58	0,82	1,14	1,54	2,2	19,0
	18	255,0	0,71	1,0	1,41	2,0	2,8	24,0	0,53	0,74	1,06	1,50	2,1	18,0
	20	314,0	0,64	0,93	1,31	1,85	2,6	23,0	0,48	0,70	0,99	1,38	1,94	17,0
	22	381,0	0,62	0,87	1,22	1,74	2,4	22,0	0,46	0,64	0,92	1,31	1,84	16,0
	24	453,0	0,50	0,82	1,16	1,65	2,3	21,0	0,44	0,62	0,86	1,24	1,72	15,4
Current in Amps per Conductor.	2	3,14	8,0	15,0	21,0	30,0	42,0	226	6,0	11,2	16,0	22,5	320	167
	4	12,6	23,0	35,0	48	71	102	640	17,2	26,0	36,0	53,0	770	473
	6	28,3	40	61	86	125	175	1170	30	46	65	94	130	870
	8	50,3	64	90	126	179	250	1810	48	67	94	134	185	1340
	10	78,7	85	120	169	240	330	2530	63	90	126	175	246	1870
	12	113,2	108	150	210	300	420	3320	80	112	158	222	310	2460
	14	154,0	132	184	260	365	510	4200	100	137	195	270	380	3100
	16	201,0	156	220	310	415	610	5130	116	165	230	310	450	3800
	18	255,0	180	260	360	510	715	6100	135	190	270	380	530	4520
	20	314,0	200	300	410	580	820	7170	150	220	310	435	610	5300
	22	381,0	240	350	465	660	930	8250	175	245	350	500	700	6100
	24	453,0	270	375	525	750	1050	9450	200	280	390	560	780	7000

only worked through for sections of 50, 100 and 150 sq mm. For the sake of comparison, the costs of transmission lines with aluminium conductors have been worked out for sections of 50, 100, 150 and 200 sq mm.

The maximum permissible stress in an aluminium conductor may be taken as 4 kg per sq mm. This again is a very conservative value, *i.e.*, it is rather less than one-half of the elastic limit of hard-drawn aluminium, but it is consistent with the figure of 10 kg per sq mm for hard-drawn copper. The specific gravities of copper

and aluminium are 8,9 and 2,7 respectively. The conductivity of hard-drawn aluminium is 60 per cent. of that of hard-drawn copper. Table LXVI. gives the temperature rise of overhead conductors at various current densities. The expansion coefficients may be taken as 0,000017 for copper, and 0,000023 for aluminium, per degree Centigrade.

The three conductors of each circuit are mounted on insulators fixed to the top of the tower, and, as the same voltage exists between any two of the three conductors, they are usually placed at equal distances apart at the vertices of an equilateral triangle so as to economise space and make the system symmetrical as regards self-induction and capacity. Let us consider the factors determining the distance apart.

Distance between Conductors.—The chief factors which theoretically govern the distance apart of the conductors are the voltage between the conductors and the diameter of the conductor. In practice, however (for pressures up to 20 000 volts), the conductors cannot be placed so near as these considerations would indicate, since arcs would often be started by pieces of wire, or stick, or by birds flying or falling against the wires. Above a pressure of 20 000 volts, the brush discharge loss necessitates a still greater distance between conductors, and above 40 000 volts the stress is so great at the surface of conductors *of small diameter* that the air resistance is broken down and a brush discharge takes place, no matter how great be the distance apart at which the conductors are placed; for instance, the smallest wire that it is possible to use at 40 000 volts is one of about 25 sq mm section.

The curve in Fig. 86, plotted from figures proposed by Esson, gives values which agree well with modern practice; the numbered points on the curve refer to actual values for certain installations, full particulars of which are given in Table LXIX. on pp. 176 and 177 at the end of this section.

Let us next consider the distance between the towers, *i.e.*, the "span" of the suspended conductors.

The Span.—The distance between the supporting towers is limited by the height of the towers, the maximum pull for which they are designed, and the regulations in force in the district traversed.

Where the transmission line is not straight, the conductors make an angle at the tower, and in this case either the spans must be short in order to make this angle as oblique as possible, or special towers capable of withstanding the strong side-pull must be erected,

The longer the span the more costly the towers, and for any given section of conductor there is a most economical span. This may be taken as between 130 and 160 meters for the usual sections of conductor employed.[1]

In the following investigations we shall take as a standard, for all cases, a span of 143 meters, that is 7 towers per km, with six conductors, *i.e.*, two circuits per tower.

Taking this value of the span and the above-mentioned sections

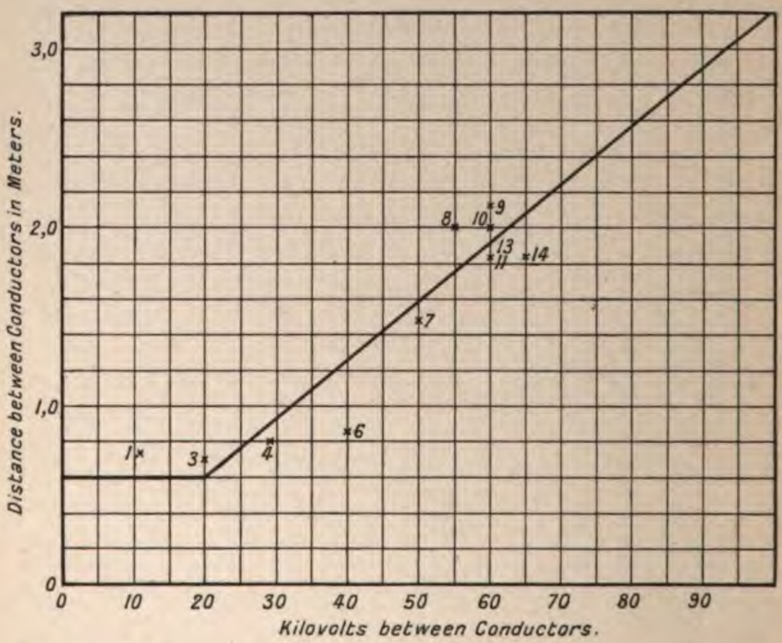


Fig. 86. Distance between Conductors, in Meters, for different Working Voltages.

of conductor, we must next determine the maximum sag which the conductor will have, and from this and the minimum height of conductor above ground we can determine the necessary height of tower.

The case of a single series of towers supporting two transmission circuits has been taken, as a steel tower construction would be

[1] For investigations concerning the "most economical span," see T. L. Kolkin in *Electrical Review*, Dec. 28, 1906; and L. Kallir in *Elektrotechnik und Maschinenbau*, Oct. 21, 1906. From considerations of the cost of poles only, the former arrives at 100—130 meters, the latter at 130—160 meters.

rarely erected for a single transmission circuit for the reasons mentioned on p. 157. The formulæ used in estimating the sag

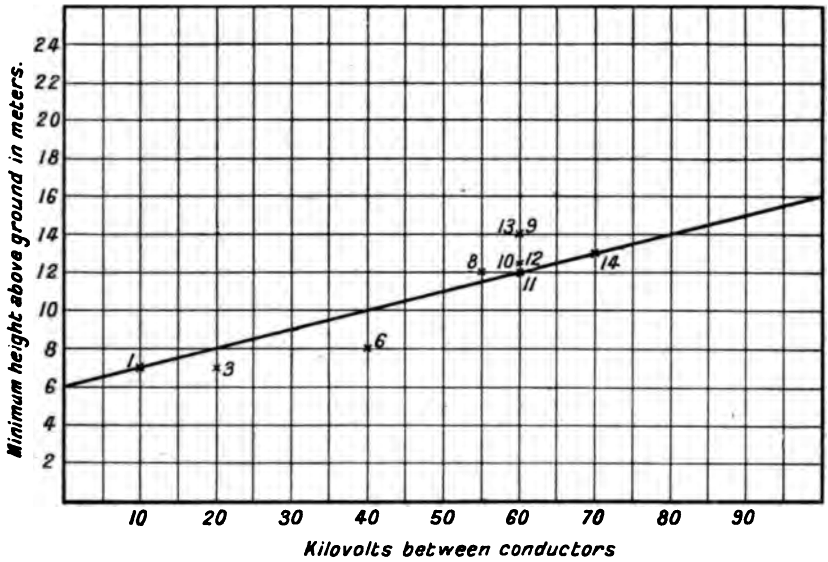


Fig. 87. Minimum Height of Conductor above Ground for different Voltages between Conductors.

and corresponding length of conductor are well known,[1] and from these the values set forth in Table LXVII. are obtained.

TABLE LXVII.

Sag of Conductors of various Section on 143 Meter Span.

Section of conductor in sq mm	25	50	100	150	200
Weight in kg per m	0,22	0,45	0,9	1,35	1,8
Wind pressure per meter (maximum)	0,56	0,77	1,08	1,33	1,55
Resultant force	0,6	0,9	1,4	1,9	2,4
Consequent sag at – 25° C (10 kg per sq mm tensile stress) in meters	6,1	4,6	3,6	3,2	3,0
Vertical sag at 45° C and no wind	6,8	5,5	4,7	4,4	4,25

The curve in Fig. 87 gives the minimum height of conductor above ground which may be taken as good practice at various

[1] For complete data concerning such calculations, see the previously mentioned papers by Kolkin and Kallir; also Kolkin, *Electrical Review*, Sept. 14 and 21, 1906, and Nachod, *Electrical World and Engineer*, Dec. 9, 1905.

TABLE LXVIII. (*a*).

Dimensions, Weights and Costs of Three-phase, Duplicate Circuit Steel Tower Transmission Lines.

Copper Lines.

Pressure between Conductors.	10 000 Volts.					20 000 Volts.					40 000 Volts.			60 000 Volts.			80 000 Volts.		
Real cross-section of copper per conductor . . . sq mm	25	50	100	150	200	25	50	100	150	200	50	100	150	50	100	150	50	100	150
Apparent cross-section of stranded conductor 1 : 0, 75 sq mm	34	67	134	200	267	34	67	134	200	267	67	134	200	67	134	200	67	134	200
Diameter of stranded conductor mm	6,7	9,2	13	16	18,5	6,7	9,2	13	16	18,5	9,2	13	16	9,2	13	16	9,2	13	16
Weight of all six conductors per km . . . . . tons	1,39	2,78	5,56	8,35	11,1	1,39	2,78	5,56	8,35	11,1	2,78	5,56	8,35	2,78	5,56	8,35	2,78	5,56	8,35
Distance between conductors, meters	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	0,6	1,25	1,25	1,25	1,9	1,9	1,9	2,6	2,6	2,6
Span in meters (7 towers per km) . . . . . meters	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143
Maximum vertical sag (45° C), no wind . . . . meters	7	5,5	5	4,5	4,5	7	5,5	5	4,5	4,5	5,5	5	4,5	5,5	5,0	4,5	5,5	5,0	4,5
Height of conductor above the ground (minimum) . meters	7	8,5	9	9,5	9,5	8	9,5	10	10,5	10,5	10	10,5	11	12	12,5	13	14	14,5	15
Length of tower (including part in ground and support for top insulator) . . . meters	17	17	17	17	17	18	18	18	18	18	20	20	20	22	22	22	24	24	24
Maximum pull on either side of tower (-20° C + wind), tons	1,5	3,0	6,0	9,0	12,0	1,5	3,0	6,0	9,0	12,0	3,0	6,0	9,0	3,0	6,0	9,0	3,0	6,0	9,0
Weight of copper per tower, tons	0,2	0,4	0,8	1,2	1,6	0,2	0,4	0,8	1,2	1,6	0,4	0,8	1,2	0,4	0,8	1,2	0,4	0,8	1,2
Weight of tower . . tons	1,0	1,2	1,6	2,0	2,4	1,1	1,3	1,7	2,1	2,5	1,5	1,9	2,3	1,7	2,1	2,5	1,9	2,3	2,7
Cost of one tower (delivered) £	16	19	26	32	38	18	21	27	34	40	24	30	37	27	34	40	30	37	43
Number of insulators per km .	42	42	42	42	84	42	42	42	42	84	42	42	42	42	42	42	42	42	42
Number of insulators per ton of copper	30	15	7,5	5	7,5	30	15	7,5	5	7,5	15	7,5	5	15	7,5	5	15	7,5	5
Cost of one insulator and pin £	0,375	0,375	0,375	0,375	0,375	0,5	0,5	0,5	0,5	0,5	0,75	0,75	0,75	1,0	1,0	1,0	1,25	1,25	1,25
Total cost of copper conductors per km. (copper at £100 per ton) . . . . . . £	139	278	556	835	1111	139	278	556	835	1111	278	556	825	278	556	835	278	556	835
Total cost of towers per km £	112	133	182	224	266	126	147	189	238	280	168	210	259	189	238	280	210	259	300
Total cost of insulators per km £	16	16	16	16	32	21	21	21	21	42	32	32	32	42	42	42	53	53	53
Total cost of auxiliary apparatus per km . . . . . . £	30	30	30	30	30	30	30	30	30	30	35	35	35	40	40	40	45	45	45
Total cost of foundation material per km . . . . £	8	10	12	14	16	9	11	13	15	17	12	14	16	13	15	17	14	16	18
Total cost of line material per km . . . . . . £	305	467	796	1119	1455	325	487	809	1139	1480	525	847	1177	562	891	1214	600	929	1251
Erection constant	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1
Total cost per km . . . . £	335	514	876	1230	1600	385	535	890	1253	1628	578	932	1295	618	980	1335	660	1022	1378
Total cost of line per ton of line copper . . . . . £	241	185	158	147	144	268	193	160	150	147	208	167	155	222	176	160	238	184	165
Cost of line per km minus cost of copper . . . . . £	196	236	320	395	490	219	257	334	418	517	300	376	460	340	424	500	372	466	543
Ratio of total cost to cost of copper . . . . . . £	2,4	1,85	1,58	1,47	1,44	2,58	1,93	1,6	1,5	1,47	2,08	1,67	1,55	2,22	1,76	1,6	2,38	1,84	1,65

TABLE LXVIII. (*b*).

Dimensions, Weights and Costs of Three-phase, Duplicate Circuit Steel Tower Transmission Lines.

Aluminium Lines.

Pressure between Conductors.	10 000 Volts.			20 000 Volts.			40 000 Volts.			60 000 Volts.				80 000 Volts.		
Real cross-section of aluminium per conductor sq mm.	50	150	200	50	100	200	50	100	150	50	100	150	200	50	100	150
Apparent cross-section of stranded conductor 1 : 0,75 sq mm	67	200	267	67	134	267	67	134	200	67	134	200	267	67	134	200
Diameter of stranded conductor . . mm	9,2	16	18,5	9,2	13	18,5	9,2	13	16	9,2	13	16	18,5	9,2	13	16
Weight of all six conductors per km . . tons	0,84	2,52	3,36	0,84	1,68	3,36	0,84	1,68	2,52	0,84	1,68	2,52	3,36	0,84	1,68	2,52
Distance between conductors . . meters	0,6	0,6	0,6	0,6	0,6	0,6	1,25	1,25	1,25	1,9	1,9	1,9	1,9	2,6	2,6	2,6
Span in meters (7 towers per km) . meters	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143	143
Maximum vertical sag (45° C), no wind. meters	10	6,5	6	10	8	6	10	8	6,5	10	8	6,5	6	10	8	6,5
Height of conductor above the ground (minimum) . . . . . . meters	6,5	10	10,5	7	9	11	9	11	12,5	10,5	12,5	14	14,5	12	14	15
Length of tower (including part in ground and support for top insulator) . . . meters	20	20	20	21	21	21	23	23	23	25	25	25	25	27	27	27
Maximum pull on either side of tower (−20° C+wind) . . . . tons	1,2	3,6	4,8	1,2	2,4	4,8	1,2	2,4	3,6	1,2	2,4	3,6	4,8	1,2	2,4	3,6
Weight of aluminium per tower . . . tons	0,12	0,36	0,48	0,12	0,24	0,48	0,12	0,24	0,36	0,12	0,24	0,36	0,48	0,12	0,24	0,36
Weight of tower . . . . tons	1,3	1,6	1,76	1,37	1,52	1,85	1,6	1,72	1,87	1,8	1,95	2,1	2,25	1,9	2,1	2,3
Cost of one tower (delivered) . . . . £	21	26	28	22	24	30	26	27	30	29	31	34	36	30	34	37
Number of insulators per km	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42	42
Number of insulators per ton of aluminium .	50	16,5	12,5	50	25	12,5	50	25	16,5	50	25	16,5	12,5	50	25	16,5
Cost of one insulator and pin . . . . £	0,375	0,375	0,375	0,5	0,5	0,5	0,75	0,75	0,75	1,0	1,0	1,0	1,0	1,25	1,25	1,25
Total cost of aluminium conductors per km (aluminium at £200 per ton) . . . . £	168	504	672	168	336	672	168	336	504	168	336	504	672	168	336	504
Total cost of towers per km . . . . £	147	182	196	154	168	210	182	189	210	203	217	238	252	210	238	259
Total cost of insulators per km . . . £	16	16	16	21	21	21	32	32	32	42	42	42	42	53	53	53
Total cost of auxiliary apparatus per km . £	30	30	30	30	30	30	35	35	35	40	40	40	40	45	45	45
Total cost of foundation material per km . £	11	13	14	12	13	15	13	14	15	14	15	16	17	15	16	17
Total cost of line material per km . . £	372	745	928	395	578	948	430	606	796	467	650	840	1023	491	688	878
Erection constant	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1	1,1
Total cost per km . . . . . . £	410	820	1020	435	635	1045	475	665	875	515	715	925	1130	540	755	965
Total cost of line per ton of line aluminium £	488	325	304	518	378	312	565	396	348	615	425	368	336	643	450	383
Cost of line per km minus cost of aluminium £	242	316	348	267	299	373	307	329	371	347	379	421	458	372	419	461

voltages. The numbered points refer, as before, to Table LXIX. on pp. 176 and 177 at the end of the section. In order to determine the total length of a tower, we must add to this value the maximum sag as found above, also two to three meters for the depth below the surface of the ground, and lastly one to two meters for that part of the structure above the lowest insulator. For example, for a 25 sq mm conductor with a maximum sag of 7 meters, and for a pressure of 10 000 volts, the minimum height above the ground

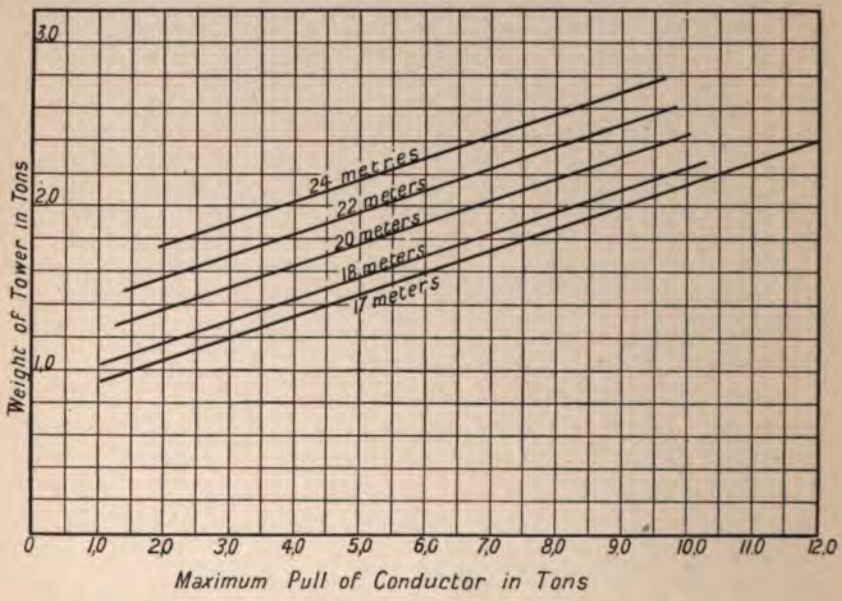


Fig. 88. Weight of Steel Towers of various Overall Lengths and for various Loads.

should be some 7 meters. Adding two meters for the embedded portion and one meter for the height above the lowest insulator, we arrive at a total length of 17 meters.

Weight and Cost of Tower.[1]—The weight of the tower will depend on the length and on the maximum pull which it must withstand. The pull exerted by the conductors on either side of the tower under the worst conditions is the product of the maximum value of the tensile stress occurring in the conductor (10 kg per sq mm) and the

[1] See also paper by D. R. Scholes on "Transmission Line Towers." Proceedings A. I. E. E., May, 1907.

total cross sectional area of all conductors. Were all the conductors of one span to break, this pull would be exerted on one side of the tower only, and the structure should be designed to withstand this stress.

The curves in Fig. 88 afford a basis for rough estimates of the weights of steel towers. In the present developmental stage of power transmission practice, such data is far from standardised, and is liable to be greatly modified. Not only the length but the width of the tower will increase with the voltage, as the conductors have to be mounted farther apart. This, however, is taken into account in the curves in Fig. 88.

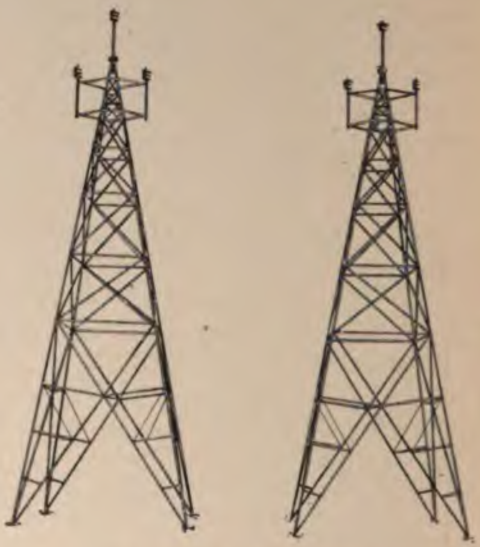
The cost of towers may be estimated on the basis of £16 per ton. A suitable form of structure is that shown in Fig. 89, C and D, which is the tower construction used on the Niagara-Toronto Line in Canada and on the Necaxa Line in Mexico. Concrete foundations will be necessary for the towers, and a figure covering the cost of the foundations must be included in estimates.

The conductors must be supported on these towers, but well insulated from them by means of umbrella-shaped or petticoat insulators specially designed for high pressures, and rigidly fixed to the steel cross-arm and well away from the steel structure.

Insulators.—The insulators used should be of porcelain, highly glazed to keep the interior perfectly dry. Insulators for high pressures are generally made in parts, cemented together with Portland cement or other suitable material. Glass has been used for insulators, one advantage being that any flaw is seen at once and elaborate testing is rendered less necessary. Porcelain is, however, mechanically stronger and is more generally used. Insulators weigh from 5 to 15 kg, and cost from 5*s*. to 25*s*. each, including the insulator pin. The insulator pin should preferably be of galvanized iron, cemented into the insulator.

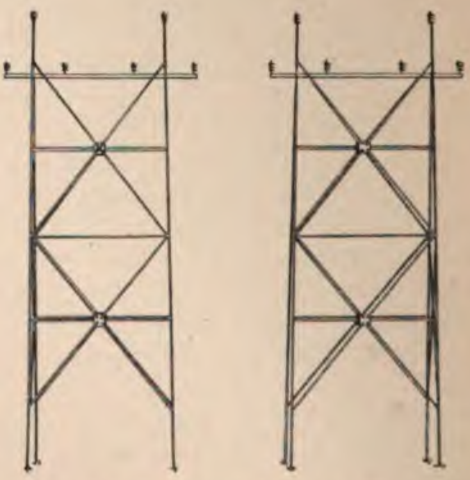
In the construction under consideration there will be, normally, six insulators on each tower, *i.e.*, 42 per km; but in the case of copper conductors of 200 sq mm section, this would provide less than four insulators per ton of copper. In this case, therefore, we must take double the number of insulators, the weight of each conductor being supported by two instead of one insulator per tower (as illustrated in Fig. 89, A). The remaining items comprised in the cost of the line are the various pieces of auxiliary apparatus, such as lightning arresters, switches, etc., the cost of which may be taken as £30 to £45 per km. All the above costs are for the

A– One Single Circuit Line.
Taylor's Fall Line.



B – Two Single Circuit Lines.
Lockport, Niagara and Ontario Line.

C—One Duplicate Circuit Line.
Niagara—Toronto Line.



D—Two Duplicate Circuit Lines.
Necaxa Line.

Fig. 89. Classification of Overhead Transmission Lines.

prepared material only, delivered on site. There now only remains to consider the cost of erection.

Erection.—The cost of erection may with sufficient accuracy for our present purposes be taken as proportional to the weight of material, and, as the cost of the material in the case of such structures is nearly proportional to the weight, 10 per cent. of the total cost of material may be taken as being sufficient to cover

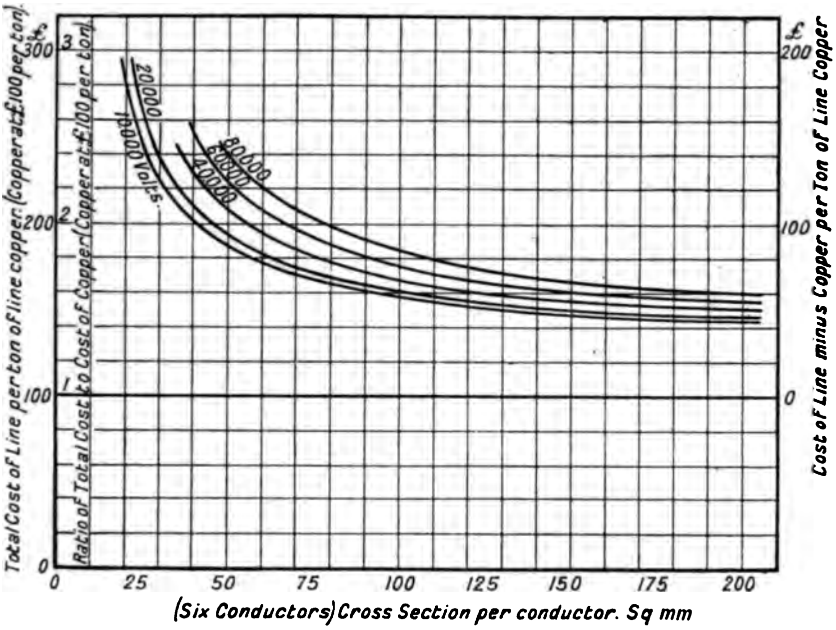


Fig. 90. Cost of Three-phase Duplicate Circuit Transmission Line (Copper Line).

erection expenses. This of course is only very rough, but it is sufficiently accurate for the present investigation.

Let us now proceed to estimate the total capital cost for duplicate circuit transmission lines at various voltages and having the copper sections given in Table LXV. Table LXVIII. (*a*) shows in detail the costs of lines for the various copper sections and the various voltages as found by employing the data and methods set forth in the preceding pages.

The results are represented graphically in Fig. 90, which shows

the cost of a transmission line of any copper section between the limiting sections for various voltages.

The cost is expressed in pounds sterling per ton of line copper, and as copper has been taken at £100 per ton, the scale on the right-hand side of the diagram gives the cost of the complete line minus the cost of the copper per ton of line copper, *i.e.*, cost of tower, insulators and erection. Thus the total cost may readily be found for any given market price of copper, as for a given section of copper and a given voltage; the combined costs of the other items may be taken as fairly constant. From these curves the ratio of

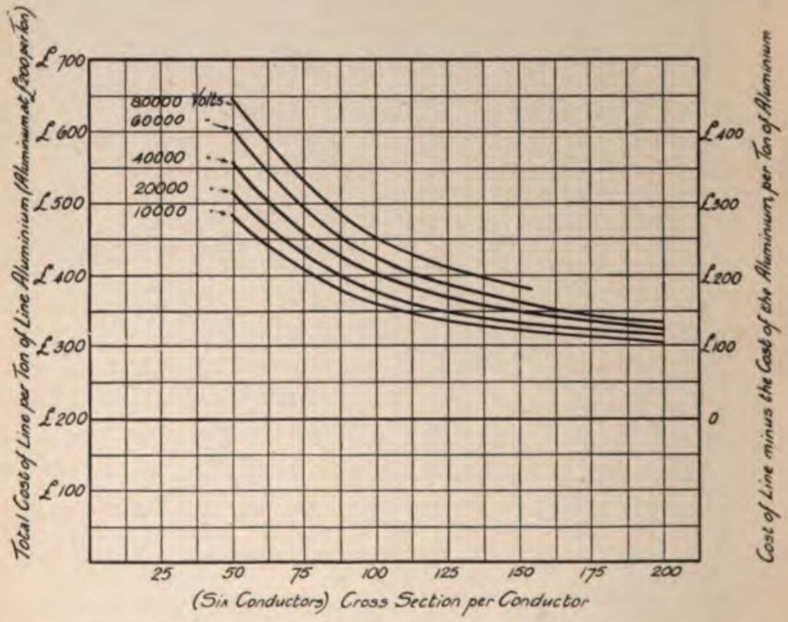


Fig. 90A. Cost of Three-phase Duplicate Circuit Transmission Line, with Aluminium Line Conductors.

the total cost of line to the cost of copper can be taken, when hard-drawn copper is at £100 per ton. This figure is only 1,5 (for the larger sections of conductor), but for the smallest section rises to 2,6.

Table LXVIII. (*b*) shows in detail the costs of aluminium lines where the price of aluminium wire has been taken at £200 per ton. The results are shown graphically in Fig. 90A. As in the case of Fig. 90, these curves can be used for any given market price of aluminium.

In Fig. 91 the total costs per km are plotted for various voltages, as a function of the section of conductor, and in this case, for the sake of comparison, the costs for the aluminium lines at 60 000 volts are also given.

These curves show that under normal conditions, and with the above prices per ton of the two metals (*i.e.*, copper £100, aluminium £200 per ton of hard-drawn wire), an aluminium line will cost

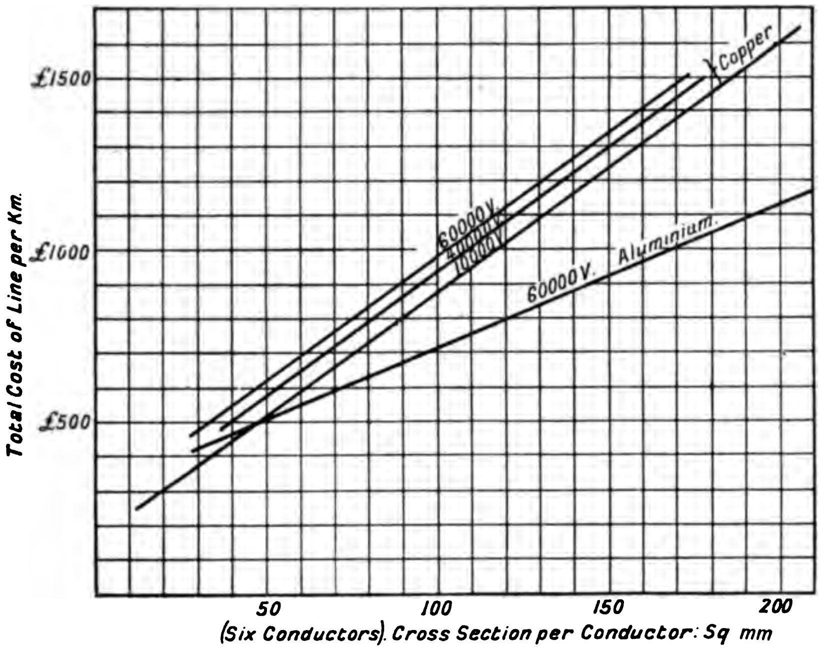


Fig. 91. COST OF THREE-PHASE DUPLICATE CIRCUIT TRANSMISSION LINES.

almost exactly as much as a copper line of equal conductivity. Thus from Fig. 91 a three-phase duplicate circuit 50 sq mm line at 60 000 volts would cost about £630 per km; an aluminium line of equal conductivity, *i.e.*, 82 sq mm, would cost about £640 per km. As another instance we may note that a copper line of 100 sq mm section would cost £980, and an aluminium line of 165 sq mm $\left(\frac{100}{0{,}61}\right)$ section would cost the same. The reason for this is that, although the aluminium conductors weigh only 50 per cent. of the copper conductors, less than one-half the tensile stress can be

allowed in the wires, and consequently, on account of this and of the larger area offered to wind pressure, the sag and consequently the height of tower must, for a given span, be greater than that with a copper conductor.

For comparisons at other than the above prices of the two metals, the curves of Figs. 90 and 90A must be used.[1]

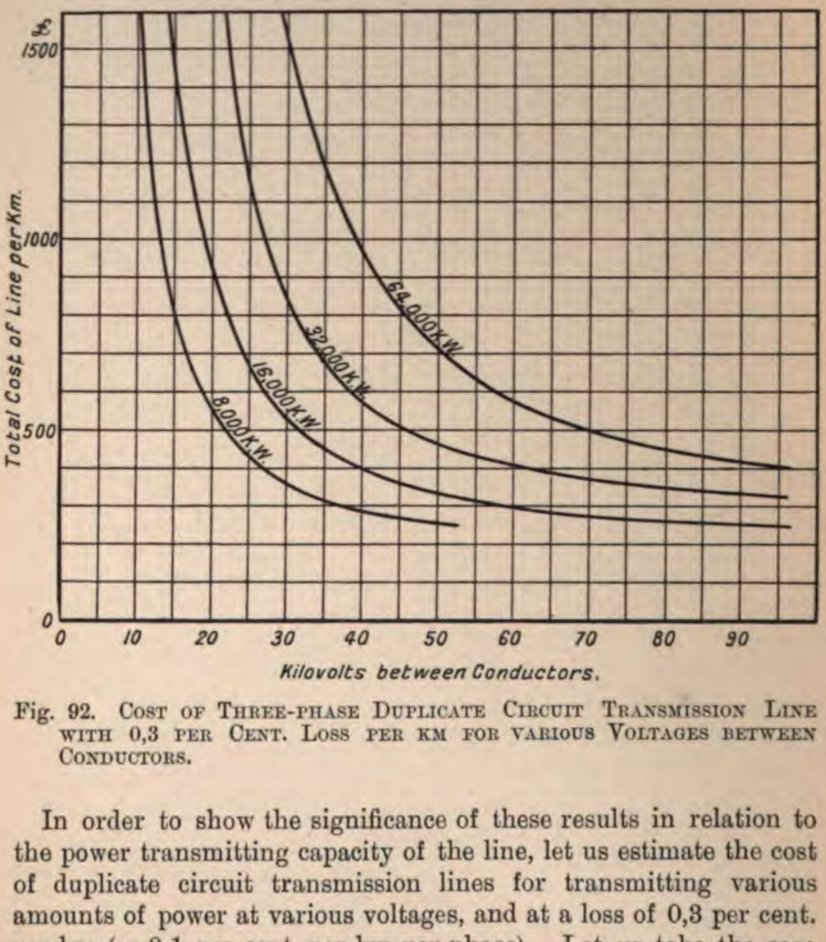


Fig. 92. COST OF THREE-PHASE DUPLICATE CIRCUIT TRANSMISSION LINE WITH 0,3 PER CENT. LOSS PER KM FOR VARIOUS VOLTAGES BETWEEN CONDUCTORS.

In order to show the significance of these results in relation to the power transmitting capacity of the line, let us estimate the cost of duplicate circuit transmission lines for transmitting various amounts of power at various voltages, and at a loss of 0,3 per cent. per km (or 0,1 per cent. per km per phase). Let us take the case of a duplicate circuit line capable of transmitting 32 000 kilowatts

[1] See footnote on next page, and for a further discussion on the subject, see *Electrical Review*, vol. 61, p. 872, November 22nd, 1907.

(*i.e.*, 16 000 kilowatts per circuit) at 30 000 volts between conductors, and with a 0,3 per cent. loss per kilometer at full load and unity power factor. Let us consider one of the two circuits:—

$$\text{Kw per phase } \frac{16\,000}{3} = 5334$$

$$\text{Volts per phase } \frac{30\,000}{1{,}732} = 17\,320$$

$$\text{Current per phase } \frac{5\,334\,000}{17\,320} = 308 \text{ amp.}$$

At a 0,3 per cent. loss per km we have:—

$$\text{Loss per km per phase} = 5\,334\,000 \times 0\,003$$
$$\text{or } 16\,000\,000 \times 0{,}001$$
$$= 16\,000 \text{ watts.}$$

$$\text{Resistance per km per phase} = \frac{16\,000}{(308)^2} = 0{,}170 \text{ ohm}$$

$$\text{Resistance of copper per centimeter cube (at } 20^\circ \text{ C.)}$$
$$= 0{,}000\;0017 \text{ ohm}$$

$$\therefore \text{ Section per conductor} = \frac{0{,}000\;0017 \times 100\,000}{0{,}170}$$
$$= 1{,}00 \text{ sq cm.}$$

From Fig. 91 the cost of a duplicate circuit line at 30 000 volts and 100 sq mm per conductor is found to be £900 per km.[1] In a similar manner the costs for other voltages and other power capacities have been estimated, and the results are shown in Fig. 92. From these curves it is clearly seen that for transmitting even as much as 8000 kw over a duplicate circuit transmission line with a loss of 0,3 per cent. per km at full load and unity power factor, little advantage is gained by employing a transmission voltage of over 50 000 volts. For long distances, where the loss must be less than 0,3 per cent. per km, or for larger amounts of power transmitted, the economical voltage will be greater.

It must be noted, also, that at high voltages and a given amount of power transmitted, the required section will fall below the

[1] With hard-drawn copper wire at £100 per ton. If the current price of hard-drawn copper wire were £70 per ton, we should make use of the curves in Fig. 90. Thus, for 100 sq mm wire at 30 000 volts, the cost of the line, minus copper, per ton of contained copper is £75. We require $100 \times 8{,}9 \times 10^{-3} \times 6 = 5{,}3$ tons of copper per km; therefore the cost of the line per km, including copper, is $(75 + 70)\,5{,}3 = £770$ per km.

TABLE LXIX.

Data of Overhead Transmission Lines.

(a) Copper Lines.

Number.	Name of Undertaking or Line.	Transmission Voltage between Conductors.	Power Transmission in Kw.	Distance of Transmission, Km.	Frequency Cycles per Second.	Generating Volts.	Diameter of Conductor, mm.	Number of Conductors.	Total Section per Conductor, Sq mm.	Distance between Conductors, Meters.	Construction of Line.	Span in Meters.	Height of Lowest Insulator above Ground, Meters.	Overall Length of Pole or Tower, Meters.	Depth in Ground, Meters.	Insulator.	Year of Commencement of Operation.	References.
1	Lancashire Electric Power Company	11 000	8000	7,5	50	11 000	9,5	6	70	0,75	Creosoted Norway fir poles with oak cross-arms	45	7	9,8	1,8	Glazed white porcelain triple pettic, iron pins	1906	*Electrical Engineer*, Sept., 1906.
2	Paderno to Milan, Italy	13 500	10 000	32	42	13 500	9	6	64		Steel lattice poles, 3 conductors per pole	60					1900	*Engineering Mag.*, August, 1901.
3	Clermond - Ferrand Line, France	20 000	3000	30	50	1000	8	6	50	0,70	Steel lattice poles, 6 conductors per pole	100	10	12	2			*Electrician*, Oct. 1905.
4	Toulon Line, France, (Société Energie Electrique)	28 000	2000	58	25	3500	6	6	28	0,8						Porcelain, iron pins	1905	*Electrical Review*, July 21, 1905.
5	Los Angeles to Engelwood	33 000	2200	134	50	750	7	6	42	0,6 (min)	Steel poles, wooden cross-arms	90		12		Porcelain, triple pettic, iron pins		*Elec. World & Eng.*, June 29, 1901.
6	Gromo to Nembro, Lombardia	40 000	3000	32	50	4000	6,5	3	33	0,85	Wooden poles and cross-arms	40	8	9	1	Porcelain	1904	*Electrical Review*, 1904, p. 498, vol. 55.
8	Missouri Power Co., Montana	55 000		105	60		8,5	3	54	2,0	Cedar poles with fir cross-arms	35	12	15	2	Glass, 2 parts	1906	*Elec. Eng.*, Dec., 1905; *Elec. World & Eng.*, July 13, 1901.
9	Syracuse Line Ontario Power Co.	60 000	3000	258	25			3	100 (?)	2,12	Steel Towers	75	14	18	3	Porcelain triple pettic, iron pins	1906	*Electrical Review*, Nov., 1906.
10	Guanajuato Line, Mexico	60 000	7500	160	60		7	3	42	2,0	Galvanised steel towers	135	12,5	15	2	Iron pins	1903	*Cassier's Magazine*, March, 1906.
11	Niagara to Toronto	60 000	9000	120	25		16	6	150	1,82	Galvanised steel towers	120	12	14	1,8		1905	*Elect. World & Engin.*, vol. 46.
12	Winnipeg Line, Manitoba	60 000	10 000	100	60	2300	9,2	6	70		Steel towers	150	12	14	2			*Elect. World & Engin.*, June, 1906.
13	Necaxa Power Co., Mexico	60 000	30 000	270	50	4000	12	12	85	1,82	Steel towers, 6 conductors per tower	150	14	17	2	Porcelain, iron pins		*Electrical Review*, Feb., 1907.
14	Grand Rapids Muskegon Power Co.	70 000	4500	65		15 000	7	3	40	1,82	Cedar or Cyprus poles	40	13	15	2	Porcelain, wood and iron pins	1906	*Elec. Eng.*, Nov. 1906; *Elec. World & Eng.*, Nov., 1906.

TABLE LXIX

Data of Overhead Transmission Lines.

(*b*) *Aluminium Lines.*

Number.	Name of Undertaking or Line.	Transmission Voltage between Conductors.	Power Transmission in Kw.	Distance of Transmission, Kw.	Frequency Cycles per Second.	Generating Volts.	Diameter of Conductor, mm.	Number of Conductors.	Total Section per Conductor, Sq mm.	Distance between Conductors, Meters.	Construction of Line.	Span in Meters.	Height of Lowest Insulator above Ground, Meters.	Overall Length of Pole or Tower, Meters.	Depth in Ground, Meters.	Insulator.	Year of Commencement of Operation.	References.
15	Shawinigan to Montreal	58 000	7500	145	30	2200	12	3	90	1,53	Cedar poles	30				Porcelain, 3 parts, hickory wood pins		*Electrical Engineer*, Jan., 1906.
16	Snoqualmie Falls to Seattle	30 000	9000	71	60	2300	6				Wood poles	45					1904	*British Alum. Co. Bulletin.*
17	Niagara Falls to Buffalo	22 000	11 000	35	25	11 000	20	3	240	0,92	Wood poles, conductor braided	34				Wooden pins	1904	*Elec. World & Eng.*, Dec., 1904.
18	Electra to San Francisco	60 000	10 000	240	60		20	3	240		Wood poles	40				Wooden pins		*British Alum. Co. Bulletin.*
19	Colgate to Oakland	40 000	11 000	230			13,5	3	116		Wood poles	40				Wooden pins		*British Alum. Co. Bulletin.*
20	Ontario to Buffalo	22 000	37 000				20	9	240		(Spans Niagara River, 640 meters)							*British Alum. Co Bulletin.*
21	Niagara, Lockport, and Ontario Power Co.'s Line	60 000	45 000	250	25	12 000	23	9	320		Galvanised steel towers, 3 conductors per tower	165				Porcelain, 3 parts, steel pins	1906	*A.I.E.E. Proceedings*, Sept., 1907.
22	Telluride Power Co., Colorado	40 000			63					1,9	Wood poles							*Cassier's Magazine*, Jan., 1905.
23	Animas Power Co., Colorado	50 000	6000	67	60	4000	8	3	50	1,84	Wood poles	76	8,5	11	1,8	Porcelain, 2 parts, cast iron pins	1906	*Electrical Review*, April, 1906.

minimum practicable section at the voltage; for example, to transmit 32 000 kw at 60 000 volts along a duplicate circuit line, a conductor of only 25 sq mm section is necessary. This section is below the minimum for this voltage, consequently either a lower voltage or a lower loss per kilometer would be taken. These plans both lead to a larger section. For the sake of comparison, details of overhead transmission lines in various countries have been collected and are given in Table LXIX.

SECTION 3.—UNDERGROUND CABLES.

For long distance transmission, underground cables are generally quite inadmissible, chiefly because the cost of the transmission line is so great as to render underground cable projects commercially impracticable. For transmission over short distances, however, cables are often used and occasionally a long transmission line is partly overhead and partly underground, the tower or pole construction being prohibited by some local authorities on the score of alleged unsightliness and insufficient safety.

Let us take the case of underground transmission with three-core lead-covered cables and let us estimate the cost of such cables for various sections of copper and for various voltages, in a manner similar to that employed in the preceding section in dealing with overhead transmission lines. Let us also consider that in all cases the neutral point of the system is effectually earthed[1] (*i.e.*, that it is at zero potential): then the working pressure between any core and the lead covering is equal to the pressure per phase, which equals the pressure between any two of the three cores, divided by $\sqrt{3}$.

In our generalised study of the subject we shall consider the case of the three cores each separately insulated to a uniform radial thickness, and with an insulation equal to one-fourth of the thickness on each core wrapped about the independently insulated group. The four remaining intermediate portions are also completely filled with insulating materials. Such an arrangement is shown in the upper diagram in Fig. 93.

The Conductor.—The conductor may be of copper or aluminium, and stranded to give greater flexibility. The stranded cable may

[1] This is a safeguard against an excessive rise in potential of any part of the system, and is advantageous so long as the E.M.F. wave of the generators does not contain the third harmonic or any multiple of the third. These harmonics, if they were present, would be the cause of capacity currents through earth.

have a circular section, if small, or if of large section, the strands should be assembled into a sector shaped section as in the second example of Fig. 93. By this latter construction, the overall diameter is much reduced, and a saving in both lead and insulation is effected.

The wire in an underground cable is not subjected to any

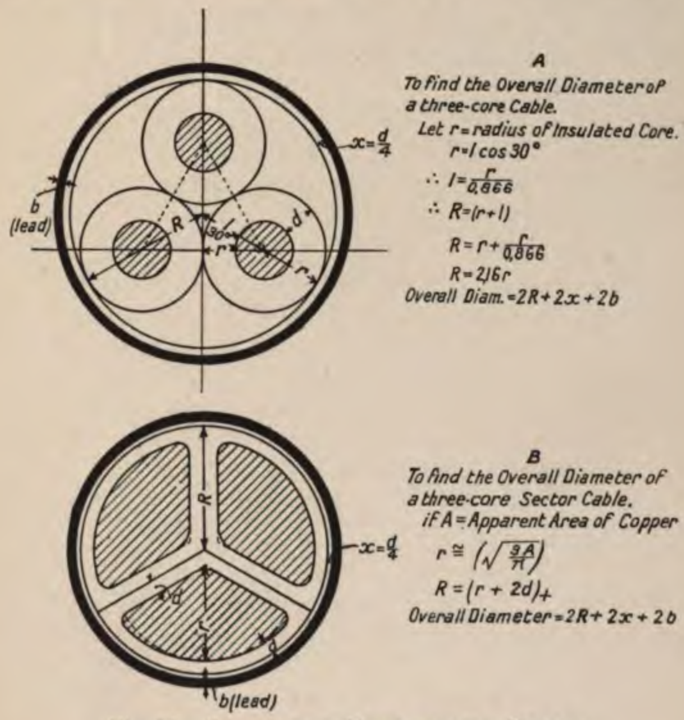


Fig. 93. SECTIONS OF HIGH-TENSION CABLES.

considerable mechanical stresses, consequently the only lower limit of size of conductor is that imposed by the radius of curvature. This is discussed in the section on insulation on p. 184.

Table LXX. gives the sections per core for various sizes of three-core cables, the cost of which we shall proceed to estimate. At a pressure of 5000 volts, no section under 150 sq mm is taken, since we are only dealing with cables of large power-transmitting capacity. For the same reason, the 25 sq mm 10 000 volt cable is omitted. For pressures of over 20 000 volts a 25 sq mm core is impracticable, as the radius of curvature is so small as to impose grave difficulties as regards insulation.

No cable with cores of over 200 sq mm section is considered after 20 000 volts is reached, as the power-transmitting capacity of such a cable would be excessive.

To supply cables at 30 000 and 40 000 volts corresponding to

TABLE LXX.

Sections of Core in Three-core Cables to which the Investigation relates.

Voltage between Cores.	Real Cross-section per Core in Sq Mm.					
5000	—	—	—	150	200	300
10 000	—	50	100	150	200	300
20 000	25	50	100	150	200	300
30 000	—	50	100	150	200	—
40 000	—	50	100	150	200	—

30 sq mm of copper, cables having aluminium cores of 50 sq mm section are taken at these voltages. For other examples of aluminium cables see p. 193.

Table LXXI.[1] gives the currents and corresponding current densities for various sections of copper, which correspond to a

TABLE LXXI.

Maximum permissible Current for Three-phase Three-core High-tension Copper Core Cables giving a Final Temperature Rise of about 25° C when laid Underground.

Section per Core, Sq Mm.	Current per Core, Amperes.	Current Density, Amps Sq Mm.
10	60	6,0
15	75	5,0
25	100	4,0
35	120	3,4
50	150	3,0
70	180	2,6
95	210	2,2
120	240	2,0
150	280	1,85
185	320	1,75
240	370	1,55
310	420	1,35

[1] In preparing this table the authors were guided by the results of the investigations of Teichmüller and Humann, which appear to give the most complete and reliable results available. See *Elektrotechnische Zeitschrift*, Nov. 22nd, 1906.

Compare also the recommendations of the "Sicherheits Kommission," *Elektrotechnische Zeitschrift*, May 16th, 1907.

maximum temperature rise of about 25° C after about ten hours' working at those densities for three-core high-tension cables laid underground. This value is already closely approached after four hours' working.

The temperature rise should not be permitted to be more than 30° C, consequently these values may be used as maximum working values.

Thickness of Insulation.—The radial thickness of dielectric necessary for a given difference of potential between the copper core and the outside lead covering, depends not merely on this difference of potential and on the dielectric strength of the insulating material, but it is also dependent on the radius of curvature of the copper core, and on certain other considerations not yet susceptible to quantitative determination, such as certain surface resistance phenomena at the contact of copper and insulation.

For homogeneous insulation, the stress which the insulation undergoes is also by no means uniform throughout the radial depth. The stress at the surface of the core is $\frac{R}{r}$ times the stress at the surface of the lead, where r is the radius of the copper core and R the radius over the insulation.[1]

[1] Notes from Jona's St. Louis Congress Paper

The potential falls from the outer surface of the conductor (where it is a maximum) to the outer surface of the insulation (where it is zero, being in contact with the lead and soil), in accordance with a logarithmic curve.

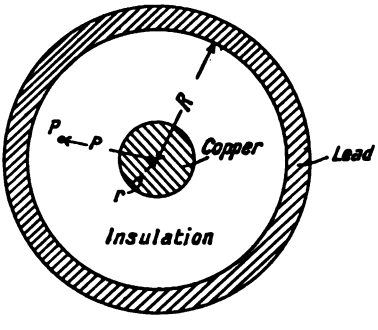


Fig. 94. Section of Single Core Cable to illustrate Fall of Potential in the Dielectric.

For Homogeneous Insulation:—

Referring to Fig. 94, we have—

Potential at point P at a distance ρ from centre, =

$$v = V \frac{\log_\epsilon \frac{R}{\rho}}{\log_\epsilon \frac{R}{r}}$$

Gradient, or rate of fall of potential $= \frac{dv}{d\rho}$

$\frac{dv}{d} = \frac{0{,}434\ V}{\rho \log_{10} \frac{R}{r}}$ = dielectric stress in volts per mm. at point P if ρ, r and R in mm. At surface of copper $r = \rho$

$$\left(\frac{dv}{d\rho}\right)_r = \frac{0{,}434\ V}{r \log_{10} \frac{R}{r}} = \text{maximum stress} = w$$

[See over.

Consequently, when settling the thickness of insulation, we are concerned not so much with the total voltage as with the maximum stress to which the insulation will be subjected. The curves in Fig. 95 show the necessary radial depth of insulation for various

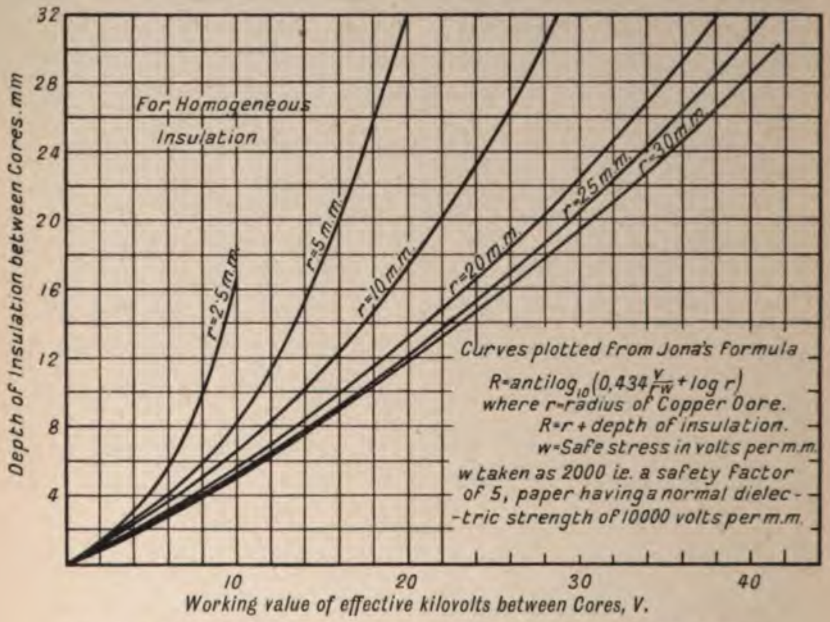


Fig. 95. INSULATION THICKNESS FOR HOMOGENEOUS CABLES FROM JONA'S FORMULA.

voltages and for various minimum radii of curvature. These curves have been plotted from the formula given by Jona.

It will be noticed that for pressures of over 20 000 volts, and for cores of normal radii, the thickness of dielectric becomes too large

---

where w is the maximum stress in volts per mm that the insulating material can safely withstand.

At surface of insulation

$$\left(\frac{dv}{d\rho}\right)_R = \frac{0{,}434\ V}{R \log_{10} \frac{R}{r}} = \text{minimum stress.}$$

Ratio of maximum to minimum stress $= \frac{R}{r}$.

NOTE.—There is a certain value of r, which for a given R gives the smallest value of maximum stress w possible.

This value of $r = \frac{R}{\epsilon} = \frac{R}{2{,}71}$.

to be practicable. It is possible, however, to reduce this depth of insulation by placing near the core a material of higher dielectric strength. This procedure is known as "grading" the insulation. Thus we can have several layers of different dielectrics, materials of higher dielectric *strength* being employed for the inner layers where the dielectric *stress* is greatest. By this means the overall diameter of the cable may be considerably reduced.

When we vary in this way the nature of the dielectric, there is

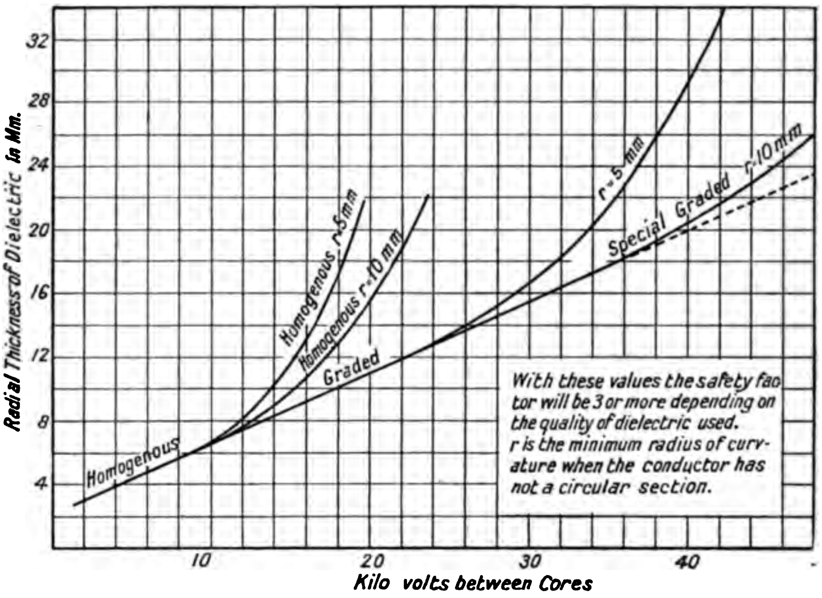


Fig. 96. THICKNESS OF INSULATION OF GRADED CABLES FOR ALTERNATING CURRENT.

another important point to be considered. This relates to the effect on the potential curve of the varying dielectric capacity.[1]

Care must be taken that the "specific capacity" of the dielectric *decreases* in proportion to its distance from the core. This has the effect of decreasing the steepness of the potential curve near the core and increasing the steepness near the lead, thus putting a more uniform stress upon the dielectric. In this way the required thickness of dielectric is further decreased.

By a combination of the above two principles, we may reduce

[1] See O'Gorman, *Journ. I. E. E.*, vol. xxx. p. 608.

the necessary thickness of material considerably below that which the curves in Fig. 95 would indicate to be necessary.

Lastly, Jona and others have ascertained experimentally that for cables with very small cores at high voltages, the insulation required is, when correctly applied, very appreciably less than that calculated, there being some other phenomena as yet unexplained. For the purposes of the following investigations, the radial thickness of the insulation will be taken from the curves in Fig. 96. A minimum radius of curvature of 3 mm will be taken for voltages over 5000, and a thin sheath of lead will, as proposed by O'Gorman and Jona, be placed round the stranded core so that it shall conform to this curvature. At 40 000 volts the diameter of core for low values of the kilowatts transmitted comes out less than this lowest value shown, and in these cases an aluminium or a tubular conductor of the minimum outside diameter might be used. For high voltages it might often be advisable to use an aluminium conductor, since the radial depth of the required insulation decreases rapidly with increasing radius of curvature of the core.

Jona has shown that if a stranded core is not covered with a lead sheath, the stress is liable to be increased to 1,2—1,4 times the amount obtaining for a smooth core. To allow for the room taken by this lead sheath, which, however, may be very thin, and also for the fact that the core is composed of stranded wire, the real copper section is increased by one third, and this figure is called the apparent section.

Since the cores are twisted, an addition of 3 per cent. is made on the length of cable in estimating the weight of copper per km. The space factor of the three-core cable is estimated thus :—

$$\text{Space factor} = \frac{3 \times \text{real cross section core}}{\text{Cross section up to the internal wall of the lead covering}}$$

Suitable thicknesses of lead covering are given in the following table :—

TABLE LXXII.

Showing Suitable Thicknesses of Lead for Three-core Cables.

Diameter of Insulated Cable in Mm.	Thickness of Lead Covering in Mm.
50	4,0
75	4,5
100	5,0

Estimation of Cost of Three-core Cable.—The cost of the materials used in the manufacture of cables will be expressed in pounds sterling per ton. Let us first estimate the weight of material used. The section and length of the cable being known, we require only the specific gravities.

The following values may be taken :—

Weight of 1 cubic dm of copper	= 8,9 kg
,, ,, ,, ,, lead	= 11,4 kg
,, ,, ,, ,, jute	= 1,2 kg
,, ,, ,, ,, impregnated paper .	= 1,2 kg

From these values the respective weights of the various materials used may be estimated.

The prices per ton of material may be taken as follows:

Copper per ton	= £95
Lead ,, ,, ...	= £20
Impregnated paper per ton . . .	= £40
Raw jute per ton	= £30

In order to estimate the Total Works Cost of the finished cable, the cost of labour and other costs must be added.

The following figures taken from O'Gorman's paper before the Institution of Electrical Engineers [1] give some idea of the proportions these costs bear to one another, but these figures will not be used in the present investigation:

TOTAL WORKS COST.

Proportioning of items (O'Gorman).

(1) *Copper.*	£
Cost of copper per ton	95
Cost of wire drawing	5
Cost of stranding	7
Shop costs and administration	10
Total cost per ton .	£117
(2) *Lead.*	£
Cost of lead per ton	20
Cost of labour	3
Cost of administration, etc.	7
Total cost per ton .	£30

[1] *Journal, I. E. E.*, vol. xxx. p. 644.

(3) *Impregnating Paper.*

	£
Cost of impregnated paper per ton . .	40
Cost of labour	10
Cost of administration, etc.	20
Total cost per ton .	£70

(4) *Jute.*

	£
Cost of jute per ton	30
Cost of labour, etc.	3
Total cost per ton .	£33

(5) *Rubber.*

Cost per ton (pure para rubber) . .	£400

For our present purposes we shall employ the following values:—

Cost of materials in the form in which they are delivered to the Cable Manufacturer.

Hard drawn copper wire . .	£100 per ton
Impregnated paper, Rubber, Jute filling (taken together) .	£40 to £60 per ton.[1]
Lead	£20 per ton
Hard drawn aluminium wire . .	£200 per ton

Using these values, we obtain the cost of material per km of completed cable.

ESTIMATION OF TOTAL WORKS COST.

Having estimated the total cost of material for any proposed cable, we shall multiply this by a constant which we shall designate as the "Works Cost Constant," in order to obtain a rough figure for the Total Works Cost of the cable per km when turned over by the Manufacturing Department to the Sales Department.

This constant will depend on the quality and quantity of labour, etc., required to manufacture the cable from the above material, and will also be affected by local conditions, cost of labour and power, composition of cable, etc. With increasing voltage, more care will have to be expended on the insulation, and as the material cost decreases with the voltage, except for extra high voltages, for

[1] The cost of the insulation is taken at £40 per ton for a 10 000 volt cable and £60 per ton for a 50 000 volt cable, as, at the higher voltages, the insulation will be partly rubber and will have to be carefully graded.

a given copper section, the value of the constant will increase with the voltage.

For a given voltage, the labour expressed as a percentage of the total cost of material will decrease with increasing copper section, as the labour required will not increase to such a degree as the outlay for material increases.

Taking these points into consideration, the curves in Fig. 97 have been deduced, showing the value of the "Works Cost Constant" for different copper sections and voltages, the curves being based on values worked out from actual cases.

Table LXXIII. gives the costs of cables corresponding to the

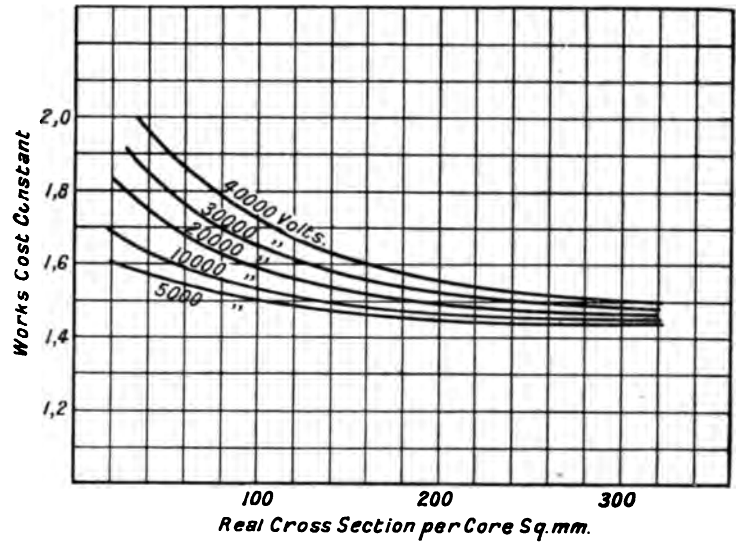


Fig. 97. Works Cost Constant for Three-core Cables, as Function of Copper Section and Voltage.

various copper sections and voltages between cores set forth in Table LXX. The various items have been estimated according to the method given in the preceding pages. The curves in Fig. 98 are plotted from these results and give the Total Works Cost of a cable of any given copper section, per core, at various voltages. The T.W.C. is expressed in pounds sterling per ton of contained copper.

The results are obtained by taking the price of copper as being £100 per ton. The price of copper varies, however, within wide

TABLE LXXIII.

Dimensions, Weights, and Costs of Three-core Cables.

Voltage between Cores.	5000			10 000					20 000						30 000				40 000				Aluminium. 30 000	Aluminium. 40 000
Real cross-section of copper per core . . . . . sq mm	* 150	* 200	* 300	50	100	* 150	* 200	* 300	25	50	100	150	* 200	* 300	50	100	150	200	50	100	150	200	50	50
Apparent cross-section . 1 : 0,75	200	267	400	67	134	200	267	400	34	67	134	200	267	400	67	184	200	267	67	134	200	267	67	67
Diameter of stranded core (if round) . . . . mm	16	18,5	22,5	9,2	13	16	18,5	22,5	6,7	9,2	13	16	18,5	22,5	4,2	13	16	18,5	9,2	13	16	18,5	9,2	9,2
Radial thickness of insulation between cores . . mm	4,5	4,5	4,5	6,5	6,5	6,5	6,5	6,5	11	11	11	11	11	11	18	17	16	16	32	26	24	22	18	32
Radial thickness of insulation round all three . . mm	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,0	1,5	1,5	1,5	1,5	1,5	1,5	2,3	2,2	2	2	4	3,3	3	2,8	2,3	4
Diameter of insulated cable mm	39	43	51	36	45	43	47	55	42	47	55	62	57	65	64	70	74	79	97	92	93	94	64	97
Space factor (not including lead covering)	0,37	0,41	0,44	0,15	0,19	0,31	0,35	0,38	0,05	0,09	0,13	0,15	0,23	0,27	0,04	0,08	0,11	0,12	0,02	0,04	0,6	0,8	0,04	0,02
Thickness of lead covering) mm	4	4	4,5	4	4	4	4	4,5	4	4	4,5	4,5	4,5	4,5	4,5	4,5	4,5	5	5	5	5	5	4,5	5
Overall diameter of cable . mm	47	51	60	44	53	51	55	64	50	55	64	71	66	74	73	79	83	89	107	102	103	104	73	107
Weight of copper per km (met tons)	4,15	5,55	8,35	1,38	2,78	4,15	5,55	8,35	0,69	1,38	2,78	4,15	5,55	8,35	1,38	2,78	4,15	5,55	1,38	2,78	4,15	5,55	0,415	0,415
Weight of insulation per km (met tons)	0,9	1,02	1,37	1,05	1,43	1,2	1,37	1,78	1,56	1,91	2,5	3,1	2,35	2,9	3,7	4,3	4,4	5,15	8,7	7,6	7,6	7,6	3,7	8,7
Weight of lead per km (met tons)	6,15	6,7	8,9	5,7	7,05	6,7	7,35	9,65	6,6	7,35	9,65	10,7	9,8	11,5	11	12	12,5	14,7	18,7	17,4	17,5	17,9	11	18,7
Total weight per km (met tons)	11,2	13,27	18,62	8,13	11,26	12,05	14,27	19,78	8,85	10,64	14,93	17,95	17,7	22,75	16,08	19,08	21,05	25,4	28,78	27,78	29,25	31,05	15,12	17,82
Cost of copper per km . . £	415	555	835	138	278	415	555	835	69	138	278	415	555	835	138	278	415	555	138	278	415	555	83	83
Cost of insulation per km . £	34	38	52	42	57	48	55	71	70	86	112	140	105	130	185	215	220	258	480	418	418	418	185	480
Cost of lead per km . . £	123	134	178	114	141	134	147	193	132	147	193	214	190	230	220	240	250	294	374	348	350	358	220	374
Total cost of material per km £	572	727	1065	294	476	597	757	1099	271	371	583	769	856	1195	543	733	885	1107	992	1044	1183	1331	488	937
Works cost constant . .	1,48	1,45	1,44	1,6	1,56	1,48	1,47	1,45	1,8	1,7	1,59	1,53	1,5	1,47	1,8	1,65	1,57	1,52	1,9	1,72	1,62	1,57	1,8	1,9
Total Works cost per km . £	850	1060	1530	470	740	885	1120	1600	490	630	930	1180	1290	1760	980	1210	1390	1690	1890	1800	1920	2100	888	1780
Total cost per ton of contained copper . . . . . £	205	190	183	340	266	214	202	192	710	457	334	284	232	211	710	435	335	304	1370	650	442	380	2140	4300
Total cost per ton of cable . £	76	80	82	58	66	73,5	79	81	55	60	62	66	73	77	61	63	66	66,5	66	65	65,5	67,5	58	64

* Indicates sector core section.

limits. For a given section of copper and a given voltage, the size of cable, and *all* costs, with the exception of that of the copper,

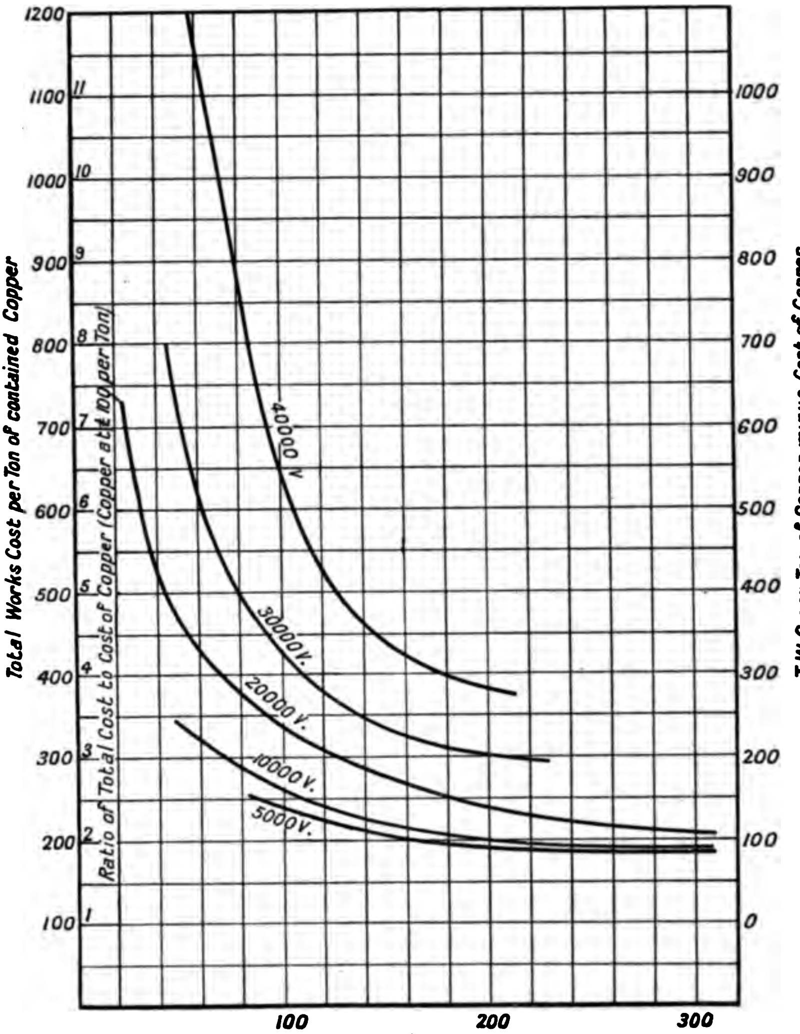


Fig. 98. Cost of Three-phase Three-core High-tension Cables.

remain constant (as the combined cost of lead, insulation and labour may be taken as fairly constant).

From the ordinates on the right of Fig. 98 we can read off the

T.W.C. per ton of contained copper, minus the cost of the copper itself. Therefore, in order to estimate the cost of a cable, we have only to read off this cost from the curve and add to it the *current price* of hard drawn copper wire per ton. This gives us the T.W.C. of the cable per ton of contained copper. Multiplying this by the total weight of copper in the line, we obtain a rough estimate for

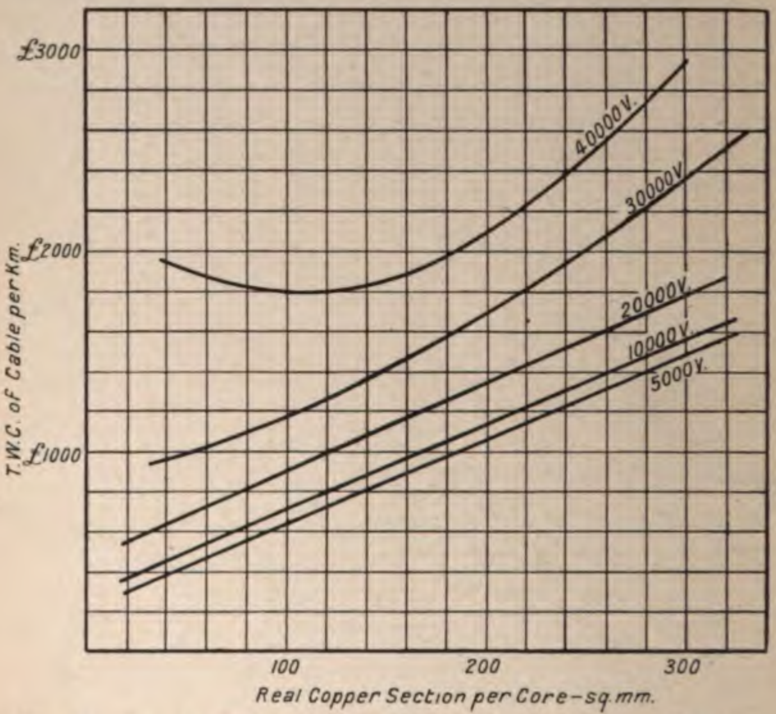


Fig. 99. COST OF THREE-PHASE THREE-CORE HIGH-TENSION CABLES.

the T.W.C. of the complete cable as turned over by the Manufacturing Department to the Sales Department. In Fig. 99 the T.W.C. of the cable *per km*, with copper at £100 per ton, is plotted for various voltages as a function of the section of conductor. As in the case of the overhead line, the significance of the results is again best shown by means of examples.

Let us, as before, take the case of transmission lines of various capacities as regards the number of kilowatts of energy to be transmitted and at various voltages, and for a loss of 0,3 per cent. per km. In this case, however, let us take one cable, *i.e.*, a single

three-phase circuit. The copper section necessary is calculated in the same way as before. From this the weight of copper per km is obtained and finally the cost per km at various voltages. The results are given in the curves of Fig. 100.

From these curves we see that with copper at £100 per ton, and with a line loss of 0,1 per cent. per km per core, a pressure of about 15 000 volts corresponds to the cheapest cable for 1000 kw, but for transmitting large amounts of power, higher voltages correspond

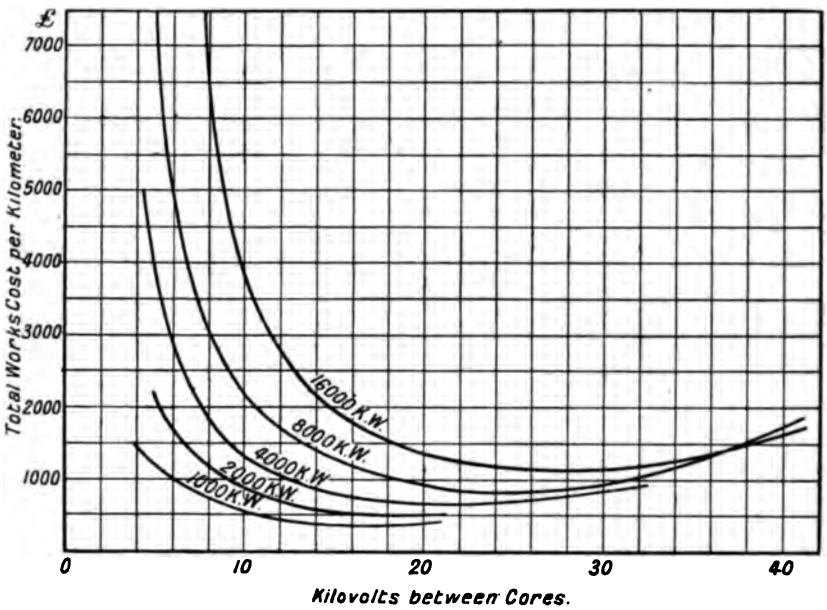


Fig. 100. Cost of Three-phase Three-core Cables at different Voltages between Cores, with 0·3 per Cent. Loss per km.

to cheaper cables. The cheapest cable for a 16 000 kw transmission works out for a pressure of 28 000 volts.

The increase in depth of insulation required for wire of small diameter causes the cost of the 8000 kw cable to be more than that of the 16 000 kw cable when a pressure of 40 000 volts is employed. The 8000 kw cable at this pressure would have been cheaper and smaller if the strands had been wound round a central core of jute, as the diameter over the thin lead sheath would have been greater.

In Fig. 101 the most economical voltage is plotted as a function

of the kilowatt transmitted per cable. These curves have been deduced directly from the curves of Fig. 100.

The curve of Fig. 102 gives the cost of cable per km per kw transmitted at the most economical voltage as a function of the kw transmitted per cable.

Insulated Cables of other Metals than Copper.[1]

Although copper has been, and is still, the recognised metal for the cores of electric power cables, the supply and the price of the

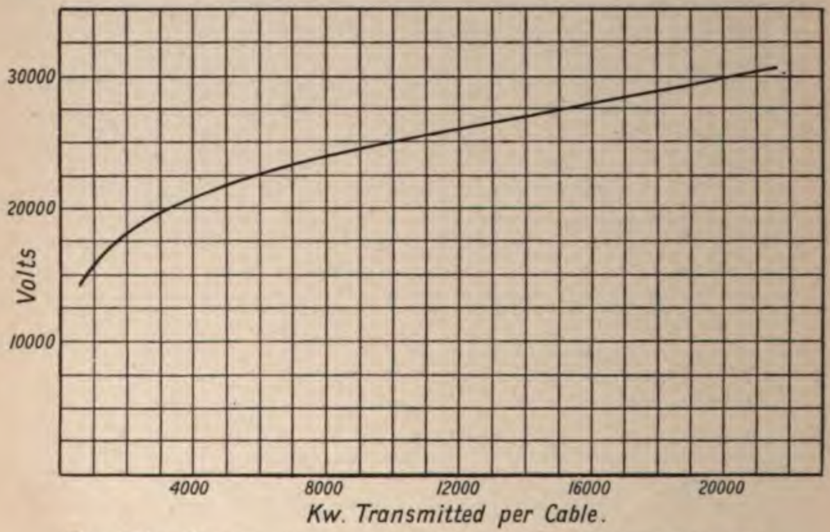


Fig. 101. Curves showing most Economical Voltage for kw transmitted per Cable at 0,3 per Cent. Loss per km.

metal are by no means steady, and there is always the possibility that another metal or alloy may become more suitable. Indeed, cables having aluminium as the conducting metal are already on the market. The curves given in Fig. 98, although intended in the first place for copper cables, can be used as a basis for estimating the cost of three-phase three-core cables with cores of any other metal. On the right-hand side of Fig. 98 we have as ordinates "the T.W.C. of cable per ton of contained copper minus the cost of the copper conductor itself," *i.e.*, the T.W.C. of a complete cable (of such a length that it contains one ton of copper) exclusive of the cost of the conductor.

[1] See also "Aluminium as a Substitute for Copper for Electrical Transmission Purposes," *Electrical Review*, vol. lxi. p. 796, November 15, 1907.

Now, for a *given section of conductor*, a cable containing one ton of aluminium will be longer than a cable containing one ton of copper, in the inverse ratio of the specific weights, *i.e.*, in the ratio of 8,9 to 2,7, or in general in the ratio:—

$$\frac{\text{Specific weight of copper}}{\text{Specific weight of metal used}}$$

For a *given section of conductor*, the cost of the insulation per unit

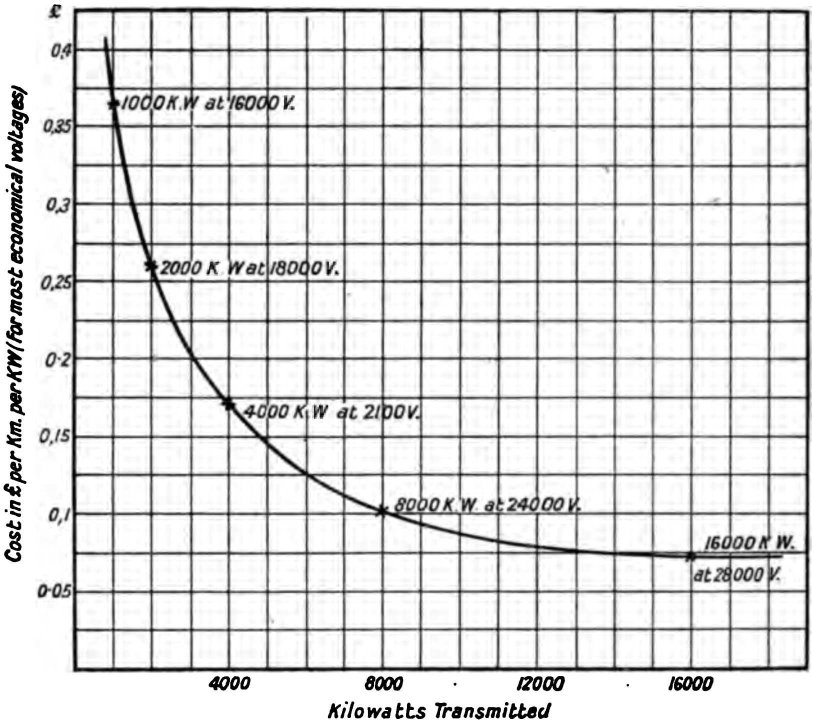


Fig. 102. Cost of Cable per km per kw Transmitted with Increasing kw (for most Economical Voltage), with 0,3 per Cent. Loss per km.

length will be independent of the metal used as conductor. Therefore, to find the "T.W.C. of cable per ton of aluminium, minus the cost of the aluminium conductor itself," we must multiply the ordinate of the right-hand side of Fig. 98 by $\frac{8,9}{2,7}$.

We have now the means of readily estimating the cost of an aluminium cable of any section.

(A.) As an example let us estimate the cost of a three-phase, three-core aluminium cable of 82 sq mm per core for 10 000 volts working pressure.

Weight of aluminium per km (allowing 3 per cent. for stranding)

$$82 \times 2,7 \times 3 \times 10^{-3} \times 1,03 = 0,685 \text{ tons.}$$

Cost of aluminium cores per km (aluminium wire at £200 per ton)—

$$200 \times 0,685 = £137$$

From Fig. 98 we find that the T.W.C. of cable *per ton of copper*, minus cost of conductor, for 82 sq mm and 10 000 volts is equal to £180.

Therefore T.W.C. of cable *per ton of aluminium*, minus cost of conductor, for 82 sq mm and 10 000 volts is equal to

$$£180 \times \frac{8,9}{2,7} = £593$$

or T.W.C. of cable *per km* minus cost of conductor

$$= £593 \times 0,685 = £406.$$

Therefore Total Works Cost of cable per km

$$= £406 + £137 = £543.$$

(B.) For the sake of comparison let us work out the cost of a copper cable of equal conductivity and for the same working pressure.

Section of copper $= 82 \times 0,61 = 50$ sq mm

Weight of copper per km $= 50 \times 8,9 \times 3 \times 10^{-3} \times 1,03 = 1,38$ tons.

Cost of copper per km (with copper at £100 per ton)

$$100 \times 1,38 = £138.$$

From Fig. 98. T.W.C. of cable *per ton of copper*, minus cost of conductor, for 50 sq mm and 10 000 volts = £240.

Therefore T.W.C. of cable *per km*, minus cost of conductor =

$$£240 \times 1,38 = £331.$$

Therefore Total Works Cost of cable = £138 + £331 = £469.

That is $\frac{469}{543} = 0,865$ times the cost of the aluminium cable.

(C.) Let us now estimate the price per ton of copper, in order that the copper cable should cost the same as the aluminium cable, when the price of aluminium is at £200 per ton.

Cost of cable to be £543.

But cost of insulation, etc. = £331 (see above).

Therefore cost of cores will be £212.

Weight of cores = 1,38 tons.

Therefore cost of copper per ton $= \frac{212}{1,38} = £154.$

(D.) Or we can estimate the price per ton of aluminium in order that the aluminium cable should cost the same as the copper cable, when copper is at £100.

Thus the cost of cable = £469.

But cost of insulation, etc. = £406.

Therefore cost of cores = £63.

Weight of cores = 0,685 tons.

I.e., cost of aluminium per ton $= \frac{63}{0,685} =$ £92.

The above results are summarised in tabular form in Table LXXIIIa.

TABLE LXXIIIa.

Comparison of Costs of Copper and Aluminium Cables.

10 000 Volt Three-phase Cable.	B	D	C	A
	Cu.	Al.	Cu.	Al.
Section per core (sq mm) .	50	82	50	82
Weight of metal per km (tons)	1,38	685	1,38	0,685
Cost of metal per ton (£) .	100	92	154	200
Cost of metal per km (£) .	138	63	212	137
Cost of insulation, manufacture, etc., per km (£) .	331	406	331	406
Total cost per km (£) . .	469	469	543	543

For very high voltages and small sections, the larger diameter of the aluminium core permits a smaller depth of insulation (see Figs. 95 and 96 on pp. 182 and 183 of this Chapter). Take for example the exceptional case of a 40 000 volt cable, 50 sq mm for copper, 82 sq mm for aluminium. The cost of complete cable works out at £1850 per km for the copper cable, and £1770 per km for the aluminium cable, *i.e.*, the aluminium cable is a little cheaper.

This is, however, a very exceptional case, and with the present prices of the metals and for normal cases, the aluminium cable will, for high-tension work, be more costly than the copper cable.

Underground Construction.—The curves in Fig. 98 give the cost of cable as delivered by the Manufacturing Department to the Sales Department, and in order to compare the total outlay for an underground with that for an overhead system we must estimate the costs of the underground construction.

The cost of the insulated cable corresponds to the cost of the

wire and insulators of an overhead system, and the cost of the underground construction corresponds to the cost of the steel tower construction, including labour in all cases. As, however, the available data for the cost of underground construction vary over such wide limits, it was decided not to include this item in the curves for the cost of cable.

The form of underground construction in most general use is that in which the lead-covered cables are drawn into vitrified clay-tile ducts, embedded in concrete, and buried 0,6 to 1,2 meters under the surface.[1] The conduit can be of either single or multiple duct

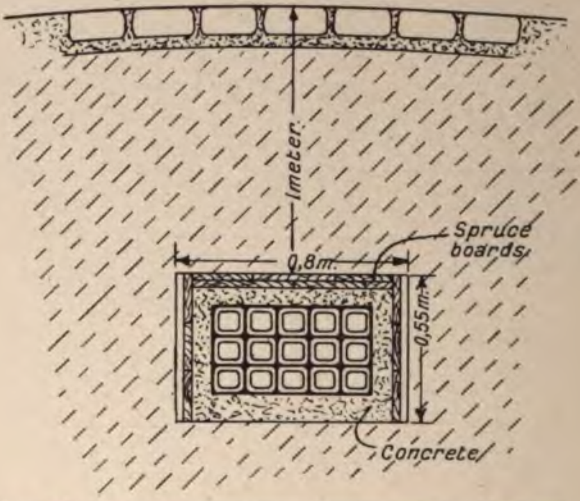


Fig. 103. SECTION THROUGH UNDERGROUND CONDUIT.

construction, the former being preferable. The holes should be square, not round, on account of the greater ease with which the cables may be drawn in in the former case. Four to six duct multiple duct conduit is customarily supplied in three-foot lengths, and two duct multiple and single duct in shorter lengths. It is preferable not to place more than one cable in a duct, but if the cables are small it may become necessary to do so in order to avoid waste of duct space.

[1] For a full description of such a conduit line, see the paper on "Underground Construction," by W. P. Hancock, read before the National Electric Light Association at Boston, May, 1904, and published in the *Western Electrician*, June, 1904. See also the paper presented to the St. Louis Congress by L. A. Ferguson, 1904 (Transactions, vol. ii.). Also a paper by W. D. Burford, *Electrical World*, Feb. 10, 1906.

The internal diameter of standard ducts varies between 8 and 12 cm, and consequently if cables having the dimensions given in Table LXXIII. are used, each will be placed in a separate duct. Manholes should be at intervals, preferably not exceeding 150 meters, in order to give easy access to any part of the cable, and also to facilitate pulling in.

When a large amount of power is to be transmitted, it is, in the case of an overhead system, sometimes thought advisable to construct a double tower line. In the same way, it is thought advisable to construct a double conduit line, the conduits being preferably laid in different streets. If too many cables are buried together, the temperature rise may be considerable, as the heat generated is not easily dissipated.

The following is an example of a 15 duct conduit, given by Hancock in the paper to which reference has been made. It is reproduced to show the relative costs of the various items. The conduit was composed of 15 single clay ducts cemented together with mortar. These were embedded in concrete (5 parts mixture, 1 part cement, 2 parts crushed stone, 2 parts sand), the thickness of the concrete being 7,5 mm at the sides and top, and 10 mm at the bottom. The boards at the side and on top were of spruce. The depth from the surface of the road to the top of the conduit was one meter (see Fig. 103). Hancock's estimate was as follows:—

Excavation and reinstalment	3,9	shillings per	cubic meter.
2,5 cm spruce boards . .	1,1	,, ,,	sq meter.
Concrete mixture . . .	25,4	,, ,,	cubic meter.
Clay ducts (delivered on site) .	0,65	,, ,,	duct meter.
Road stone block paving on concrete base (pitch filling)	9,5	,, ,,	sq meter.

Taking these values the cost per meter of conduit worked out as follows:—

Excavation and reinstalment . .	5,2	shillings.
Spruce boards	2,0	,,
Concrete mixture	4,6	,,
Clay ducts (delivered) . . .	9,8	,,
Stone block paving	9,9	,,
Engineering expenses (labour, etc.) .	10,5	,,
	42	shillings.

i.e., £2100 per km (see table).

Table LXXIV. gives the total cost for conduit laying as given by various authorities.

TABLE LXXIV.

Estimates of Total Cost for Conduit Laying.

Authority and Reference.	Total Cost of Conduit per Km.	Total Cost per Duct Km.	Component Costs. Cost of Excavating and Reinstating per Km.	Cost of Material for Conduit and Labour on same, per Km.	Cost of Road Material and Labour on same, per Km.	Number of Ducts.	Particulars of Construction and Location.
	£	£	£	£	£		
Highfield, *Journal I. E. E.*, p. 496, vol. 38	620	207	—	—	—	3	Stoneware conduit laid along country roads
Andrews, *Journal I. E. E.*, p. 529, vol. 38	220	220	—	—	—	1	Stoneware duct laid in concrete in country districts
Watson, *Journal I. E. E.*, p. 529, vol. 38	320	107	110	210	—	3	Duct conduit in country district
Burford, *Elect. World*, Feb. 10, 1906	810	202	165	265	390	4	Clay tile conduit embedded in concrete brick-paved road
	940	157	180	370	390	6	
	1100	137	290	420	390	8	
Springer, *Elect. World*, Feb. 10, 1906	560	140	—	—	—	4	Conduit under macadam road
	780	130	—	—	—	6	
	1120	280	—	—	—	4	Conduit under asphalt road
	1440	240	—	—	—	9	
Ferguson, St. Louis Congress, 1904	880	220	—	—	—	4	Clay conduit under stone-block paved road
	1110	185	—	—	—	6	
	1080	270	—	—	—	4	Clay conduit under asphalt road
	1320	220	—	—	—	6	
Hancock, *Western Electrician*, June, 1904	2100	140	264	1320	516	15	Clay conduit under stone-block paving

As a basis for estimating the cost of any conduit line, the figures in Table LXXV. are of service. These figures are deduced from data given in the above-mentioned papers.

To this must be added the cost of pulling in the cable, which may be taken as £20 to £50 per cable per km, depending on the size of cable, also the cost of the manholes, about six per km, and each costing from £15 to £35, depending on the size of the manhole.

Section 4.—The Efficiency of the Transmission Line.

On page 4 Kelvin's law was stated as follows:— "Maximum economy is obtained when the annual cost at the generating station,

of the power wasted in transmission, is equal to the interest, depreciation and maintenance of the transmission line." To this, however, should be added, "when the cost of the transmission line may be expressed as a function of the copper section, without any constant figure."

In the case of an underground conduit line there is a large figure for the cost of the underground conduit and trench. This figure remains practically constant for all sections of copper, and consequently a modification must be made in this case, the maximum economy being obtained at a higher efficiency than that indicated by the precise wording above set forth.

If the figure for interest, depreciation, and maintenance could be

TABLE LXXV.

Approximate total Cost of laying Single duct Clay Conduit in Pounds Sterling per Duct per Km.

Number of Ducts.	No Paving.	Stone Block Paving with Pitch and Pebble Joints at 10*s.* per Sq Meter.	Asphalt Paving at 17*s.* per Sq Meter.
1	220	500	700
2	140	300	450
4	110	200	260
6	90	160	220
9	90	140	190
12	90	130	170

resolved into two components, a constant component and a variable component, then the efficiency for maximum economy would be that for which the variable component is equal to the value of the wasted energy (see Fig. 103A). To show the influence of the efficiency of the line on the cost of transmission, the following case has been considered.

An annual transmission of 50 million kw hr over distances of 25, 50 and 100 km, under the following conditions:—

Power factor 0,9.

Cost of energy at generating station 0,5 pence per kw hr.

Both overhead and underground lines are considered, a duplicate circuit transmission line being taken in all cases, *i.e.*, a single tower line, carrying two three-phase circuits, or a single underground conduit containing two three-core cables.

To show the method employed, let us work out two examples, one for an overhead line and one for an underground line.

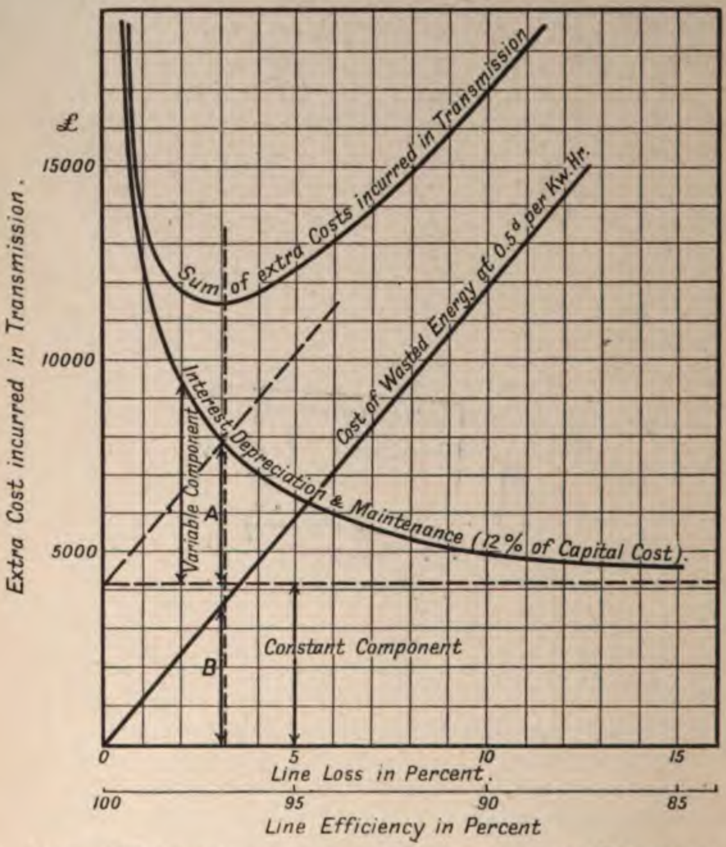


Fig. 103A. DETERMINATION OF MOST ECONOMICAL LINE EFFICIENCY FOR TRANSMISSION OF 50 MILLION KW HR PER YEAR OVER A DISTANCE OF 25 KM. (Two Three-core Cables (20 000 Volts between Cores) laid in One Underground Conduit.)

A.—Overhead Line.

Take the case of a 20 000 volt transmission over a distance of 50 km, and 50 million kw hr delivered annually.

i.e., an average of 5700 kw delivered,
or 2850 kw per circuit,
or 950 kw per conductor,

Power factor = 0,9.

Therefore kva per conductor = 1055 kva.

PLATE X.

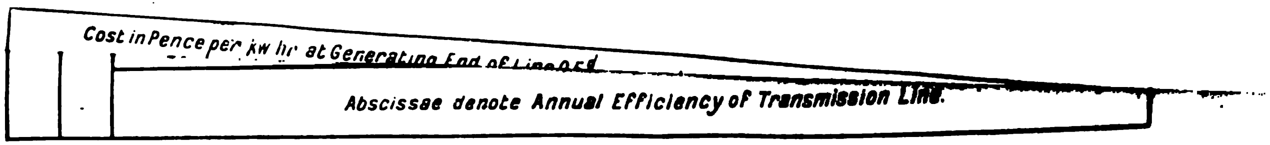


Fig. 104. CURVES SHOWING THE MOST ECONOMICAL EFFICIENCY FOR TRANSMISSION LINES.

[To face p. 201.

Volts per phase = 11 530 volt.

Therefore amps per conductor = 91,5 amp.

Take the case of an annual efficiency of 96 per cent.

Then watts lost per conductor 40 000 watts.

Total resistance per conductor $= \frac{40\ 000}{(91,5)^2} = 4,79$ ohms, or 0,096 ohms per km. This corresponds to a copper section of $\frac{0,175}{0,096} = 182$ sq mm.[1]

This gives a weight of 1,68 tons of copper per km, or for 6 conductors and 50 km, 504 tons.

With copper at £100 per ton:—

Total cost of copper = £50 400.

From Fig. 90 the ratio of total cost of line to the cost of copper at 20 000 volt, 182 sq mm section is 1,5.

∴ total cost of line = £75 600.

For an overhead line the interest, depreciation and maintenance may be taken at 16 per cent., *i.e.*, £12 100.

Cost of 50 million kw hr = £104 000.

Cost of kw hr lost = £4500.

Therefore total cost of the 50 million kw hr at the receiving end is £120 600, which is 0,58d. per unit. This value is plotted in Fig. 104.

The other points on the curves of Fig. 104 have been calculated in a similar manner.

B.—Underground Lines.

As before, let us take the case of a 20 000 volt transmission over 50 km at 96 per cent. annual efficiency.

Watts per core = 40 000 watts.

Corresponding to 0,096 ohms per km as before.

This corresponds to a copper section of $\frac{0,185}{0,096} = 194$ sq mm.

The specific resistance is taken higher in the case of underground cables, as the average temperature will be higher than that of an overhead conductor.

An aggregate weight of 540 tons of copper is obtained. With copper at £100 per ton, the total cost of copper is equal to £54 000.

[1] If the "Load Factor" is assumed to be 0,5, then the maximum current per core will be 183 amps, and the current density only 1 amp per sq mm; *i.e.*, about one-half the maximum permissible, as given in Table LXXI., p. 180.

From Fig. 98 the ratio of total cost of the cables to the cost of the copper, at 20 000 volt, 194 sq mm section, is 2,4.

Total cost of cables = £129 500.

From Table 97, the cost per duct km for underground conduit in a country district is £140.

For 50 km of two-duct conduit, cost will be £14 000.

Taking 6 manholes per km at £25 each, cost will be £7500.

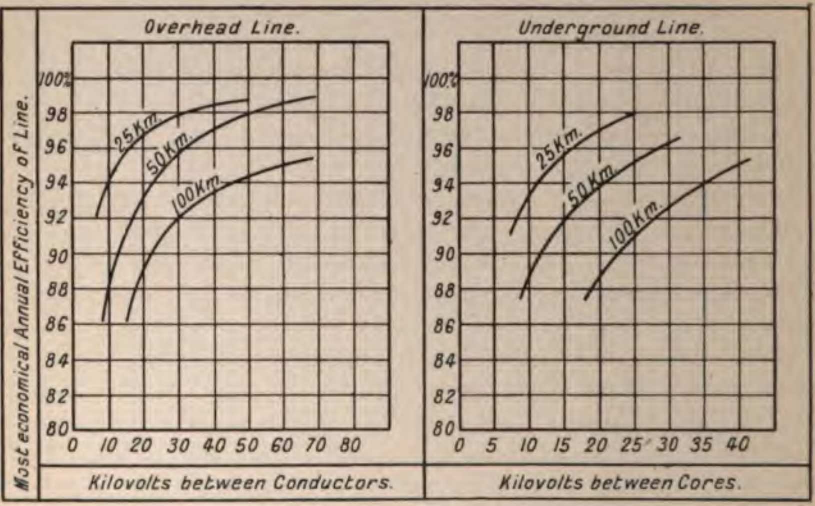


Fig. 105. Curves showing most Economical Efficiency of Line for Annual Transmission of 50 Million kw hr at Various Voltages.

And cost of drawing in the two cables at £35 per cable per km will be £3500.

Therefore total capital cost is £154 500.

For an underground line the interest, depreciation and maintenance may be taken at 12 per cent., *i.e.*, £18 550.

As before, cost of 50 million kw hr = £104 000.

As before, cost of kw hr lost = £4500.

Therefore total cost of the 50 million kw hr at the receiving end is £127 050, which is 0,611d. per kw hr.

The other points on the curves have been calculated in a similar manner.

The complete set of curves is given in Fig. 104. From these curves the curves of Fig. 105 have been deduced. These show the most economical line efficiency as a function of the line voltage for the particular cases considered.

CHAPTER IX

THE HIGH-TENSION CONTINUOUS CURRENT SERIES SYSTEM

THE high tension continuous current series system of transmitting electrical power is by some engineers considered to offer advantages over the three-phase high tension alternating current parallel system.

Since 1889, when M. Thury put down his first system, rapid strides have been made in the design of the apparatus employed, and there are now several plants in existence, most of which are on the so-called "ring" system employing a complete copper circuit.

Table LXXVI. gives in tabular form a list of installations on this system, and contains particulars of the leading details. This table is taken from a paper by J. S. Highfield.[1] To this paper the reader is referred for a detailed description of the system and of the apparatus used in connection with it. In the paper, a special case is taken of a transmission scheme in a district as represented in Fig. 106, and a comparison is made between an alternating current three-phase system and the Thury continuous current series system. The generating plant, transmission line, and sub-stations are included in the comparison.

As a further instance of the estimation of the cost of underground transmission lines, let us estimate the costs for these two systems, *i.e.*, of the constant current, continuous current, high-tension system, and the constant potential alternating current high-tension system, and let us compare the results with those arrived at by Highfield. It will also be interesting to again make the comparison of the two systems, using our own estimates for the transmission lines. Let us further revise the figures for the generating plant, so that they shall be consistent with the estimates and principles laid down in earlier chapters of this treatise.

The power station, with a capacity of 7000 kw, is, in both cases,

[1] "The Transmission of Electrical Energy by Direct Current on the Series System," by J. S. Highfield, *Journal I.E.E.*, vol. xxxviii., p. 471.

TABLE LXXVI.

Installations Employing the High-tension Continuous Current Series System.

Description of Undertaking.	Year of Commencement of Working.	Line Current, Amps.	Total Length of Circuit, km.	Particulars of Machine Units.					Total Line Pressure, Volts.	Remarks.
				No.	Volts.	Kw.	Revs.	Total Output.		
Ste. Acquedotto de Ferrari-Galliers (Italy), Genes	1889	45	120	18	—	—	—	630	14 000	Ring transmission
Wasserwerke Zug (Switzerland)	1891	50	24	5	1600	89	320	400	8000	Ring ,,
Papeteries de Biberist (Switzerland)	1893	40	37	2	3400	—	—	272	6800	
Communes du Val de Travers (Switzerland)	1895	65	35	3 1	2600 1300	186 93	260 450	590	9100	Ring ,,
Ste. d'Eclairage Electrique (Brescia, Italy)	1895	50	52	3 2	1500 3000	—	—	525	10 500	
Ste. Romande d'Electricite (Switzerland)	1895	50	36	4	3500	—	—	700	14 000	Ring ,,
Commune de la Chaux de Fonds et du Locle (Switzerland)	1896	150	52	7	1800	288	300	1890	12 600	Ring ,,
Usines Electriques d'Eisenbourg (Hungary), Ikervar, Steinamanger	1896	65	65	6	1500	112	260	585	9000	Ring ,,
La Papelera Espanola Renteria (Spain)	1896	65	28	3 2	2600 2740	186 194	—	865	13 280	
Ste. Industrielle d'Electricite Rieti (Italy)	1896	30	60	4	3000	—	—	360	12 000	
M.V.T. Dunand à Batoum (Russia)	1899	50	20	2	1300	—	—	130	2600	
Usines Electriques d'Eisenbourg (Hungary), Ikervar-Sopron	1899	40	120	4	2500	112	—	400	10 000	Ring ,,
Mines de Plomb, Linares (Spain)	1900	60	60	3	3500	238	320	630	10 500	
St. Maurice-Lausanne	1902	150	112	6*	2250	373	300	4000	27 000	Straight transmission 56 km. The line is tapped twice before reaching Lausanne, to supply local loads
Moutiers-Lyon	1906	75	360	4*	7200	582	300	4300	57 600	Straight transmission of 180 km consisting of 170 km of overhead wire and 10 km of underground cable, the underground cable being at the extremity of the line and working at the full pressure

* Each unit consists of two generators.

situated on the edge of the area to be supplied. In the case of the alternating current system, this is by no means the most suitable location. The cables are assumed to be laid along country roads. Their locations are indicated in Fig. 106, the full lines representing the continuous current cable routes, and the dotted lines the

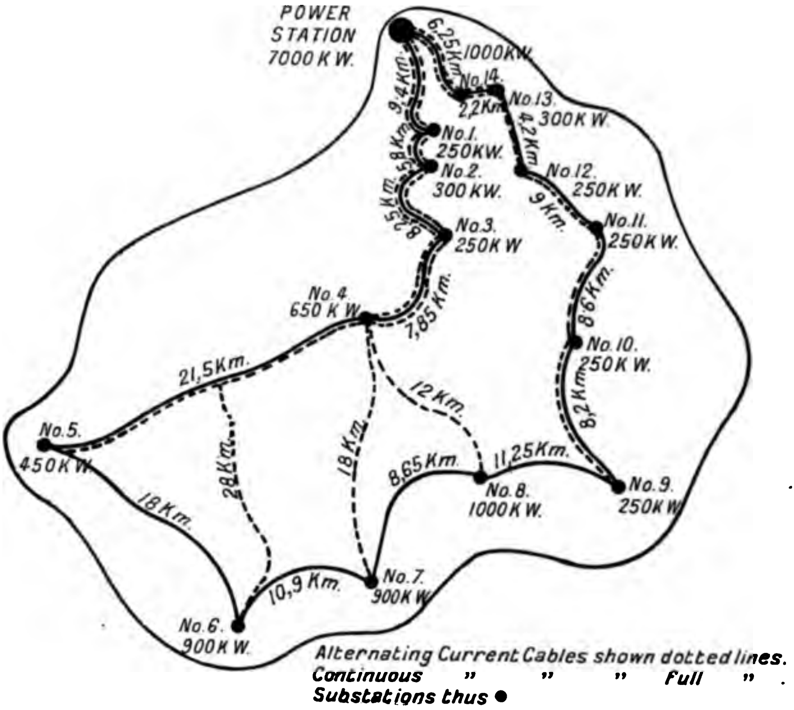


Fig. 106. Diagram of Typical Bulk Supply Area.

alternating current cable routes. The sub-stations are indicated by the small black spots.

The alternating current system is the three phase star system, with the neutral point of the system earthed. The voltage between cores is taken at 20 000 volts. The continuous current system, with 100 000 volts total pressure, is earthed at the middle point, consequently the insulation between core and lead sheath must be sufficient to withstand a working pressure of 50 000 volts.

Let us first consider the transmission line, and let us begin with the cables employed for the alternating current system. From the

generating station to sub-station 4 there are two three-core cables, section per core 48,5 sq mm; from the generating station to sub-station 13, two similar cables, and from sub-station 13 to sub-station 12 one such cable, giving a total length of 84 km of this 48,5 sq mm three-core cable.

The cost of these cables may be estimated as follows:—

Section per core	48,5 sq mm.
Tons of copper per core per km	0,445
Tons of copper per km	1,335
Cost of copper at £100 per ton	£133,5

From Fig. 98 ratio of cost of 20 000 volt lead-covered cable to cost of contained copper = 4,75

Therefore cost of cable = £634 per km. (Highfield gives £650 per km.)

Cost of 84 km of this cable = £53 200.

The cable connecting the other sub-stations has a section per core of 32,2 sq mm, and a total length of 106 km.

Section per core	32,2 sq mm
Tons of copper per km	0,885
Cost of copper per km	£88,5

From Fig. 98 the ratio of the cost of 20 000 volt lead-covered cable to the cost of the contained copper = 5,8

Therefore cost of cable = £512 per km. (Highfield gives £560 per km.)

Cost of 106 km of this cable = £54 400.

We cannot make use of Fig. 98 to estimate the cost of the continuous current cable, but we can estimate the cost in the same way as was done in Chapter VIII. In this case there is only one cable 135 km long, with a single core of 64,5 sq mm. This core will be stranded, and will thus have an apparent section of about 87 sq mm and a diameter of 10,5 mm.

The first question to consider is the thickness of insulation necessary. So great a thickness as that indicated in Fig. 96 will not be required. For a sine wave alternating e.m.f. curve, the ratio of the maximum to the effective value of the e.m.f. is 1,41 : 1, and if the maximum voltage determines the thickness of insulation necessary, then for any given insulating material the dielectric strength for continuous current is 1,41 times that for alternating current, *i.e.*, the ratio of the dielectric strength for continuous current to that for alternating current is 1,41 : 1.

It has been alleged, however, that the effect of the alternating stress is to still further lower the dielectric strength. Although very little is known concerning the matter, the advocates of the continuous current high-tension system have taken the ratio as 2 : 1. (See curves and figures in Highfield's paper.) On this basis, the insulation thickness for the 50 000 volt continuous current cable should be the same as that for a 25 000 volt alternating current cable.

Referring to the curve of Fig. 96, p. 183, the required thickness is, on this latter basis, seen to be 14 mm. The cable exhibited by Highfield at the Institution of Electrical Engineers had an insulation thickness of 14 mm and was intended for a working pressure of 50 000 volts.

We can now proceed to estimate the cost of this cable.

Section of core	64,5 sq mm
Weight of copper per km	0,59 tons
Cost of copper per km	£59 tons
Section of insulation	1079 sq mm
Specific gravity	1,2
Weight of insulation per km	1,3 tons
Cost of insulation at £45 per ton	£59
Thickness of lead	4 mm
Weight of lead	6,1 tons per km
Cost of lead per km at £20 per ton	£122

Total cost of material per km = £59 + £59 + £122 = £240.

Taking the T.W.C. as 1,5 times the cost of material:—

Cost of cable per km delivered by manufacturer is

$$1,5 \times 240 = £360,$$

which is the cost given by Highfield.

$$\text{Cost of 135 km of this cable} = £48\ 700.$$

The cost of the underground construction may be estimated from Table LXXV., given in Chapter VIII., as follows:—

For the alternating current system:

40 km of two duct conduit
110 km of single duct conduit.

For the continuous current system:

135 km of single duct conduit.

Assuming a stone block paving for the road, or a macadam road costing about the same, the cost per duct-km for a single duct conduit is (from Table LXXV.) £500, and for a two duct conduit £300 per duct km.

Consequently:

For the alternating current system—

		£
Cost of 84 km of 48,5 mm section cable	=	53 200
Cost of 106 km of 32,2 mm section cable	=	54 400
Cost of 40 km two duct conduit at £600 per km	=	24 000
Cost of 110 km single duct conduit at £500 per km	=	55 000
Drawing in 190 km of cable at £25 per cable per km	=	4750
150 km of trench with six manholes per km at £20 each	=	18 000
Total		£209 350

Highfield gives £199 000 as the total cost.

For the continuous current system—

	£
Cost of 135 km of 64,5 mm section cable	48 700
Cost of 135 km of single duct conduit at £500 per km	67 500
Cost of pulling in 135 km of cable at £25 per cable per km	3370
Cost of 135 × 6 manholes at £20 each	16 200
Total	£135 770

Highfield gives £124 300 as the total cost.

The data on which Highfield based his generating station costs are set forth in Tables LXXVII. and LXXVIII. These data are open to the following criticisms:—

I. Larger units should have been taken in the case of the alternating system and smaller units in the case of the continuous current system. The largest sets yet employed in continuous current series systems are the 600 kw sets installed in 1906 for the Moutiers-Lyon plant, and each of these sets is made up of two 300 kw generators. No other sets yet installed are of over 400 kw aggregate rated output.

II. As a consequence of I., the cost for buildings should be less for the alternating, and more for the continuous current system, than the values given by Highfield.

PLATE XI.

.E LXXIX.

sed Costs.

Alternating Current System.

Total Capacity.	14 000 Kw.	37 500 Kw.	110 000 Kw.
No. of units and size (normal rating)	4 3500 kw 12 000 volts	6 6 250 kw 15 000 volts	12 9200 kw 20 000 volts
Buildings, including chimneys	£37 600	£85 000	£240 000
Generating plant	£80 000	£188 000	£490 000
Switch gear . .	£5250	£7900	£16 700
Boilers, auxiliaries and coal handling pumps .	£66 000	£157 000	£475 000
Total cost . .	£188 850	£437 900	£1 221 700
Cost per kw . .	£13,5	£11,7	£11,1

E LXXX.

sed Costs.

Continuous Current System.

Total Capacity.	14 000 Kw.	37 500 Kw.	110 000 Kw.
No. of units and size (normal rating)	24 585 kw 45 amperes 4000 volts	62 600 kw 135 amperes 4500 volts	184 600 kw 240 amperes 2500 volts
Buildings, including chimneys	£56 000	£120 000	£360 000
Generating plant	£168 000	£410 000	£1 200 000
Switch gear . .	£2000	£3000	£5000
Boilers, auxiliaries and coal handling pumps .	£74 000	£180 000	£535 000
Total cost . .	£300 000	£713 000	£2 100 000
Cost per kw . .	£21,4	£19,0	£19,0

[To face p. 208.

III. For the same reason this will also be the case with the cost of generating plant.

IV. This is also the case with the switch gear, the cost of which is very dependent upon the number of units into which the total plant must be subdivided.

V. Boilers, auxiliary and coal handling plant should, even in Highfield's original plan, have been taken as of higher cost for the continuous current plant, since the larger number of smaller units entail greater steam consumption. Also the low efficiency of a constant current plant at light loads requires more kw hr to be sent out from the generating station for a given quantity delivered to the customers than with a constant pressure system.

In this continuous current series system the load is varied by varying the voltage, whilst the current remains constant; consequently the transmission system losses are also constant for all loads. Hence it is, that the efficiency of the transmission system is low at low loads and high at overloads.

Figures revised to take these various considerations into account are set forth in Tables LXXIX. and LXXX.

The cost of the sub-stations with a total capacity of 7000 kw was given by Highfield as £70 000 in each case. This figure is reasonable and may be taken uncorrected.

Table LXXXI. gives the total costs as given by Highfield and Table LXXXII. gives the revised figures.

From Table LXXXII. it is seen that, as regards capital costs, the continuous current system has, in this particular case, a small advantage over the alternating current system. If, however, the costs of the separate items are compared, it is seen that the cost of the generating station is very much less for the alternating current system, and that it is due only to the high costs of the transmission lines, particularly the alternating current line, that the total capital cost is lower for the continuous current system.

Now, if the transmission were overhead (and this would enable us to use a much higher transmission voltage for the alternating current), the cost of the transmission line would be less than the cost of the sub-stations, *i.e.*, less than £70 000 in each case, and although the continuous current line would again cost less than the alternating current line, the difference would not be by any means sufficient to offset the advantage on the alternating current scheme due to the lower cost of the generating station, which is £56 000 lower for the alternating current than for the continuous current scheme.

With an overhead transmission, consequently, the total capital cost would, for the case considered by Highfield, be less for an alternating current transmission system.

As regards operating costs, the continuous current series system is also at a great disadvantage, as pointed out by several engineers who participated in the discussion, since the line loss is just as great

TABLE LXXXI.

Highfield's Total Costs of Series System and of Alternating System.

	A. C.	Per Kw.	C. C.	Per Kw.
Power station of 7000 kw (A. C. includes step up transformer)	£119 000	£17,0	£140 000	£20,0
Sub-stations of 7000 kw.	£70 000	£10,0	£70 000	£10,0
Line of 7000 kw . .	£199 000	£28,4	£124 220	£17,7
Total . . .	£388 000	£55,4	£334 220	£47,7

TABLE LXXXII.

Revised Total Costs of Series System and of Alternating System.

	A. C.	Per Kw.	C. C.	Per Kw.
Power station of 7000 kw (A. C. includes step up transformer)	£105 000	£15,0	£161 000	£23,0
Sub-stations of 7000 kw.	£70 000	£10,0	£70 000	£10,0
Line of 7000 kw . .	£209 350	£30,0	£135 770	£19,5
Total . .	£384 350	£55,0	£366 700	£52,5

at light load as at heavy loads, and if the line is proportioned for, say, a loss equal to 10 per cent. of the energy delivered to the line from the generating station at the rated load, 20 per cent. of the energy delivered from the generating station will be wasted in line loss at half load, and 40 per cent. at quarter load.

In the parallel system, on the contrary, the line loss with decreasing load is a decreasing percentage of the total energy

transmitted. Thus, if the full load line loss is 10 per cent., then the line loss at half load is only 5 per cent., and at quarter load $2\frac{1}{2}$ per cent. If, for the two systems, the line loss is plotted as a

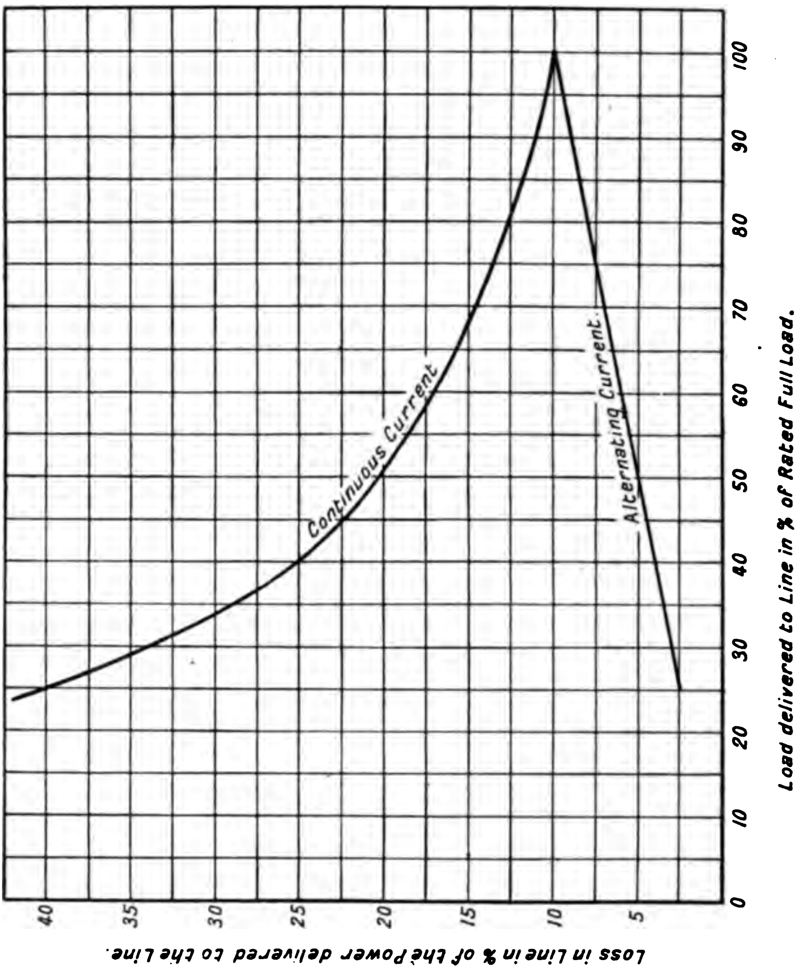


Fig. 107. Transmission Loss as a Percentage of Load for Continuous and Alternating Current Systems.

function of the load, the results, neglecting losses in transformers and motor generators, are as shown in Fig. 107.

Thus for the series system the line loss has to be proportioned for a very small percentage loss at rated load. In the case worked out by Highfield, the line loss at rated load was 3 per cent.

The transmission line would cost still more, for the continuous current system, were the ratio of the dielectric strengths for continuous and alternating current, and for a given insulating material, taken as 1,41 : 1, instead of as 2 : 1. While the use of the latter ratio appears necessary in order that estimates for the continuous current system may compare at all favourably, no data worthy of serious consideration has yet been brought forward in its support. So far at least as relates to tests of the disruptive strength of air, while certain points on the curves obtained by M. Thury bear out his contention, other points on these same curves show a ratio of only 1,4 : 1, and even less, as can be seen from Fig. 108, which shows these curves rearranged to facilitate comparison. The ratio is plotted in the lower row of curves as a function of the sparking distance.

It will be noticed that, with the exception of the plate to point experiments, the ratio is always less than 1,5 : 1. As is well known, tests on insulating materials are often very misleading, and the isolated tests mentioned in Highfield's paper do not afford by any means sufficient evidence to justify the ratio of 2 : 1.

The whole issue of the commercial advantage of the continuous current series system for power transmission rests on this point; or rather, this is one point which it is absolutely necessary to establish. Hence it is the more surprising that, after the lapse of so long an interval, we are not as yet in possession of confirmatory data from many sources. Here is a matter which could with advantage be investigated by the National Physical Laboratory. In fact, in Mr. Rayner's paper recording the results of some investigations at the National Physical Laboratory[1] are given the results of tests of the dielectric strength of air and of certain materials when subjected to two different periodicities—namely, 36 and 50 cycles. The dielectric strength increased very distinctly with the frequency, but there appeared no conclusive ground for knowing that this might not have been due to change of wave form. Indeed, everything on record in this line of work emphasises the danger of drawing hasty conclusions. There must be no room for reasonable doubt, since such data must form the basis for the design of the insulation of transmission cables.

There is ascribed to the continuous current system of working the further advantage that there is no dielectric hysteresis loss

[1] See "Journal Institution Electrical Engineers," vol. 34, p. 613.

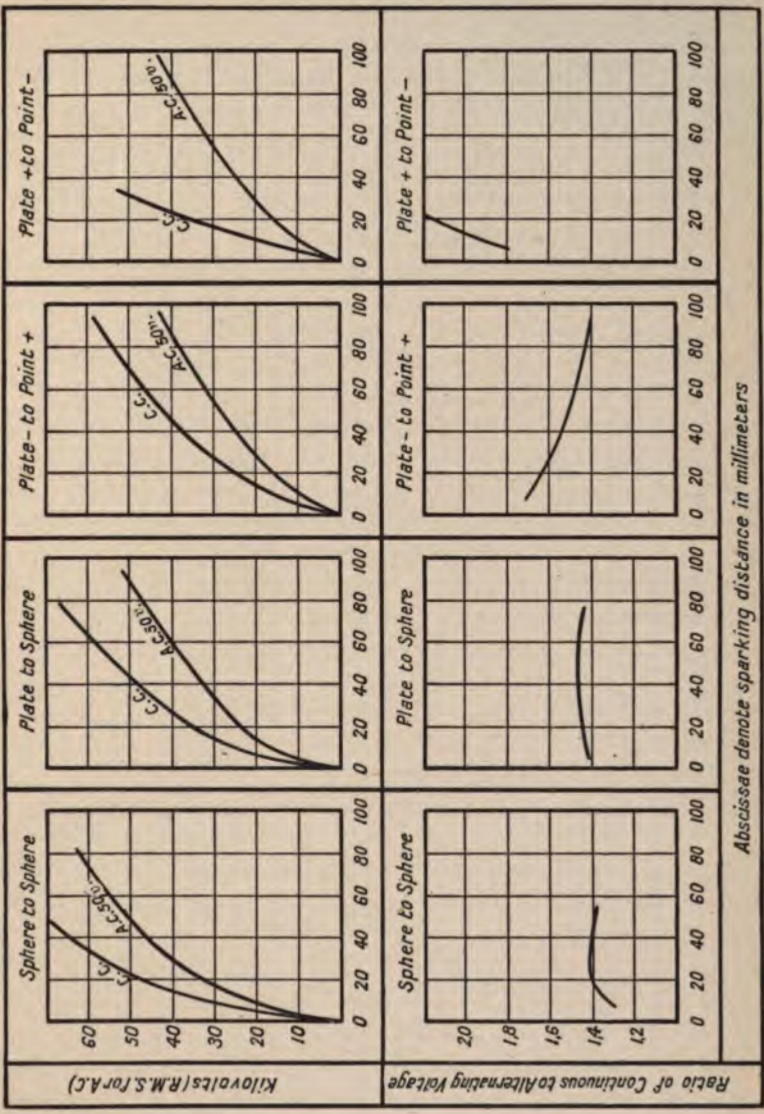


Fig. 108 Thury's Tests of Sparking Voltages for Continuous Current and Alternating Current in the Air.

in the material of the insulation. Here, again, we are touching upon a subject which has been much neglected, considering its great importance. The term dielectric hysteresis was suggested by Steinmetz in 1892. To quote from that author's "Theory and Calculation of Alternating Current Phenomena," second edition, p. 145:--

"While the laws of magnetic hysteresis are fairly well understood, and the magnitude of the effect known, the phenomenon of dielectric hysteresis is still almost entirely unknown.

"It is quite probable that the loss of power in the dielectric in an alternating electrostatic field consists of two distinctly different components, of which the one is directly proportional to the frequency, analogous to magnetic hysteresis, and thus a constant loss of energy per cycle, independent of the frequency; while the other component is proportional to the square of the frequency, analogous to the loss of power by eddy currents in the iron, and thus a loss of energy per cycle proportional to the frequency."

A good many physicists have worked at the problem since that time, but the practical man is still left without the necessary data for his purpose. $I^2 R$ losses in the insulation are frequently ascribed to dielectric hysteresis. This is a very natural error, in consequence of the rapid rate at which the true ohmic resistance of most insulating materials decreases with increasing temperature; 6° to 10° C temperature increase suffices, in most cases, to halve the insulation resistance. Thus we may, to fix ideas, say that the insulation resistance is halved for every 8° temperature increase. A 40° C temperature rise is thus likely to halve the insulation resistance five times, the value at the 40° C higher temperature being of the order of $\frac{1}{2^5} = \frac{1}{32}$, or, say, something like 3 per cent. of its original value. There will always be a minute current flowing through insulations subjected to differences of voltage, and this I V loss, small as it may be initially, is located in a substance of very low thermal conductivity. If the internal portions heat ever so little, the consequent decrease in insulation resistance will be followed by a greater current, a greater loss, and increased rate of heating, and this will be concentrated at the weakest point. This occurrence will often be sufficient to account for the breakdown, and it will not be any less serious with continuous current of a given effective voltage.

As to the additional heating due to "dielectric hysteresis," and not

occurring in continuous current systems, the practical engineer has but very scanty data for his work. The National Physical Laboratory could render a service of great value by carrying out a series of exhaustive tests on these points. We must have some better explanation than has yet been vouchsafed, and a better supply of experimental data, before we can feel reconciled to the plan of cutting down the insulation thicknesses in cables for the continuous current series systems of power transmission. As it is precisely in the cost of the transmission line where this system must make up for its greater cost in other directions, notably at the generating station, it is clear that the commercial utility of the system is dependent upon whether or no 3000 volts per millimeter thickness of insulation gives a sufficient safety factor for cables for a 50 000-volt plant of this type.

The matter of the safety factor which should be provided for cables employed in systems of different types, in itself constitutes a problem of great difficulty. For 11 000-volt three-phase transmission systems, at least double normal working pressure is invariably required to be sustained for one hour by the cable as installed. Are we to take a higher or a lower safety factor for cables for continuous current high-tension power transmission?

The inductance of the high-tension series line itself will be relatively small compared with the inductance of the machines and apparatus comprised in the series system. The inductance of a set of sub-station series motors of 7000 kw aggregate capacity on a line of, say, 100 miles length, will be of the order of at least 500 henrys. It is hardly reasonable to suppose that human ingenuity can yet provide against occasional interruptions of the circuit while carrying full load current. Let us take this current at 70 amperes for a voltage of 100 000, and let us assume, for purposes of argument, that the current is reduced in half a second from 70 amperes to zero, *i.e.*, that it is reduced at the *average* rate of 140 amperes per second. Then the reactance voltage amounts to—

$$\frac{2\pi}{1{,}41} \times \frac{0{,}25}{0{,}50} \times 500 \times 70 = 100\,000 \text{ effective volts.}$$

At the instant of breaking, however, the rate of decrease of current will be much greater than the average rate, and the momentary voltage may thus be far in excess of the above figure.

Few of us have escaped the experience of sustaining through our bodies the discharge of the field circuit of dynamos excited with continuous current. Even in the case of small machines, the result is

of an order of violence corresponding to very many times the normal pressure across the field coils. Recollections of this sort will serve to confirm mathematical estimates of the order of magnitude of these induced voltages. It is to be anticipated that should a continuous current series system on a really large scale ever be undertaken, "subtleties" will be much more in evidence than has been the case with alternating current transmission systems. It is very much to be doubted whether the factor of safety of two, which has generally sufficed for alternating current plants, will not have to give place to considerably higher values in continuous current series power transmission systems when underground cables are used. In this case the chief point of alleged commercial advantage, namely, the transmission line, will have to come in for radical reconsideration.

In Field's highly illuminating paper, read before the Glasgow Section of the Institution of Electrical Engineers some few years ago, the frequent occurrence of breakdowns on continuous current systems was considered from the standpoint of a potential wave sent into a circuit on closing a switch. As this wave of potential advances into the new circuit, it is shown how the "potential front," in entering the apparatus in the circuit, subjects the insulation between turns and between layers to stresses many times in excess of the normal stresses. It is not necessary that the circuit be actually completely opened or completely closed, for, to quote from the paper:—

"These potential fronts may be created at any point of the circuit by suddenly altering the potential at that point, *e.g.*, by short-circuiting, grounding, and the like."

What could be more pertinent to the subject under consideration than the above statement? To cut out motors in the series system, they are short-circuited. If it is a sub-station containing a couple of 4000-volt motors which is cut out of service, the instantaneous disturbance of the system is comparable to an abrupt and large change in the inductance of the circuit, and the nature of the consequences is well known.

The possible immunity of the Thury systems, as so far installed, from troubles of this sort is not reassuring, for they are all small systems, ranging from 300 to 4000 kw total capacity each. In only two of them is the line pressure over 15 000 volts, and in only one of them are the individual generators of more than 400 kw rated capacity. Thus the inductance effects and the total pressures

involved are in no sense commensurate with the values which are being discussed in connection with prospective work, and it behoves engineers who contemplate going in for larger work with this system not to disregard the consequences of cutting the insulations too fine.

Behrend's views with relation to the Thury system are of considerable interest. On p. 45 of *Cassier's Magazine* for May, 1907, there is recorded the following:—

"In the category of the *forced* ideas is to be placed the idea of transmitting large volumes of power by means of high potential continuous current. That such things can be done is unquestionable, but it is equally unquestionable that to do them by means of high potential continuous current is *unreasonable.* The intuition of the experienced engineer, which is, as it were, the consolidated experience of many years, will guard him against becoming too deeply wrapped up in schemes of this sort. We heard of high potential continuous current when the problem of the best means of transmitting the power of Niagara was discussed; we have heard of it again recently in connection with the transmission of power from the Victoria Falls. *These are ideas which cannot hold their own, though they persistently crop up like weeds which would fain take the place of useful vegetation.*"

CHAPTER X

ELECTRIC TRACTION CALCULATIONS

Speed-time Diagrams.—In electric traction calculations it is convenient to employ speed-time diagrams, which are diagrams comprising curves plotted with speed as ordinates and with time as abscissæ. In Fig. 109 is given a typical speed-time diagram for a train operating over a line with an average distance of one kilometer between stops. The diagram is plotted with speed in

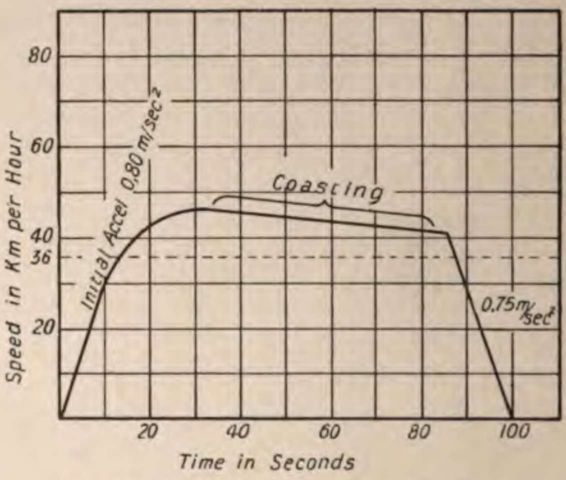


Fig. 109. Typical Speed-time Diagram.
1 Stop per Km. Average Speed = 36 Km per Hour.

kilometers per hour as ordinates, and with time in seconds as abscissæ; and it is seen that 100 seconds elapse between start and stop. Since there are 3600 seconds in one hour, the average speed from start to stop is

$$\frac{3600}{100} \times 1 = 36 \text{ km per hour.}$$

"*Average*" *Speed and* "*Schedule*" *Speed.*—The use of the term "average" speed is applied to the mean speed from start to stop.

The mean speed *including stops* is termed the "schedule" speed. If, in the present instance, each stop is of 15 seconds' duration, then $(100 + 15) = 115$ seconds elapse from the moment of starting out from one station to the moment of starting out from the next station, and consequently the *schedule* speed is only

$$\frac{100}{115} \times 36 = 31{,}3 \text{ km per hour.}$$

Importance of Brief Stops for Short and Fast Runs.—Had the duration of stop been 30 seconds, then the schedule speed would have been only

$$\frac{100}{130} \times 36 = 27{,}7 \text{ km.}$$

The results for other durations of stops are shown in Table LXXXIII.

TABLE LXXXIII.

Showing, for a 1 km Run at an Average Speed of 36 km per Hour, the serious Effect on the Schedule Speed of increasing the Duration of Stop.

Duration of Stop.	Schedule Speed.	Ratio of Schedule Speed to Average Speed.
0	36,0	1,00
15	31,3	0,87
30	27,7	0,77
45	24,8	0,69
60	22,5	0,63

With one stop per 2 km, but at the same average speed, the effect is far less serious, as also for one stop per km but with half the average speed—*i.e.*, with an average speed of only 18 km per hour. These conditions apply in Tables LXXXIV. and LXXXV.

TABLE LXXXIV.

Showing the Effect of the Duration of Stop for one Stop per 2 km and an Average Speed of 36 km per Hour.

Duration of Stop.	Schedule Speed.	Ratio of Schedule Speed to Average Speed.
0	36,0	1,0
15	33,5	0,93
30	31,3	0,87
45	29,4	0,82
60	27,7	0,77

TABLE LXXXV.

Showing the Effect of the Duration of Stop for one Stop per 1 km, and an Average Speed of 18 km per Hour.

Duration of Stop.	Schedule Speed.	Ratio of Schedule Speed to Average Speed.
0	18,0	1,0
15	16,75	0,93
30	15,65	0,87
55	14,7	0,82
60	13,85	0,77

The effect of duration of stop for various stoppages and for various average speeds is shown graphically in the curves in Figs. 110 and 111.

Alternative Speed-time Curves.—None of the relations to which

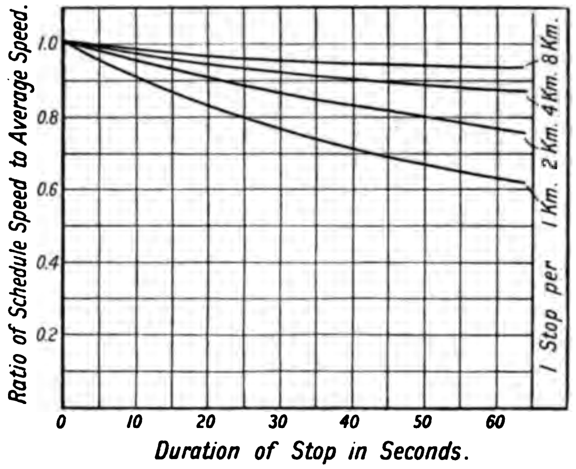


Fig. 110. Graphical Representation of the Degree of Importance of the Duration of Stop, and the Number of Stops, on the Schedule Speed, for an Average Speed of 36 km per Hour and for Various Distances between Stops.

allusion has as yet been made are affected by the substitution of alternative speed-time curves, so long as they all have the same mean ordinate from start to stop, and so long as the same time elapses from start to stop.

Fig. 109 corresponds to an initial acceleration of 0,80 m per

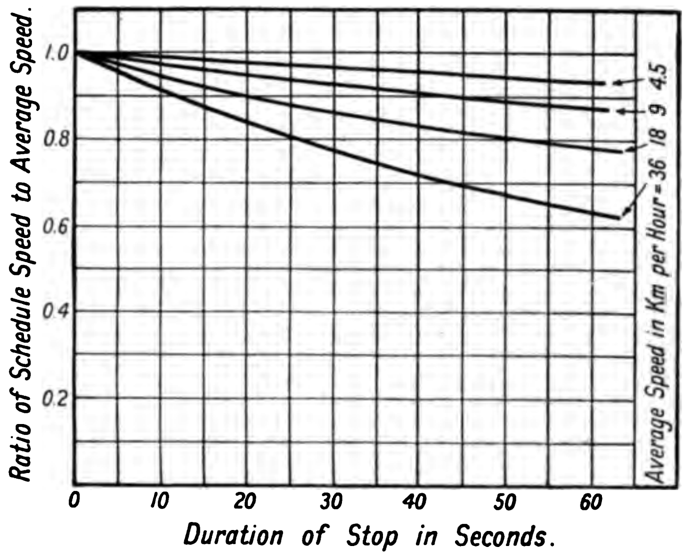


Fig. 111. GRAPHICAL REPRESENTATION OF THE DEGREE OF IMPORTANCE OF THE AVERAGE SPEED ON THE SCHEDULE SPEED FOR 1 STOP PER KM.

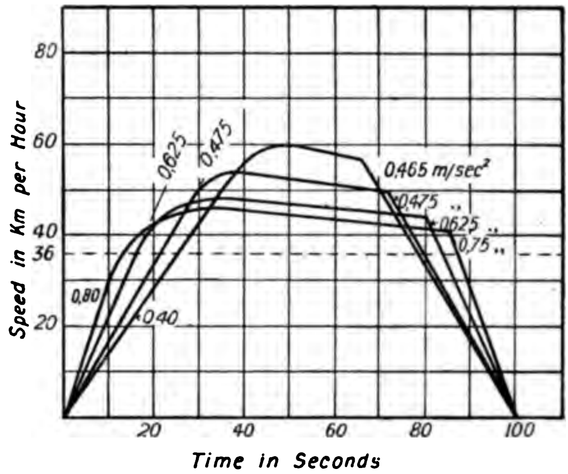


Fig. 112. SPEED-TIME DIAGRAMS FOR A 1 KM RUN AT AN AVERAGE SPEED OF 36 KM PER HOUR.

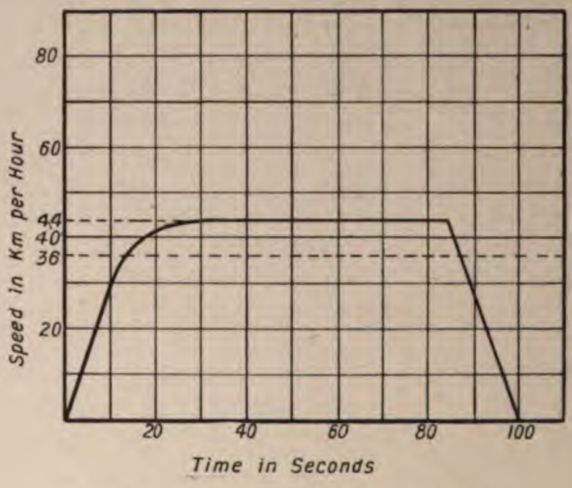


Fig. 113. MODIFIED SPEED-TIME DIAGRAM.
1 Stop per km. Average Speed 36 km per hour.

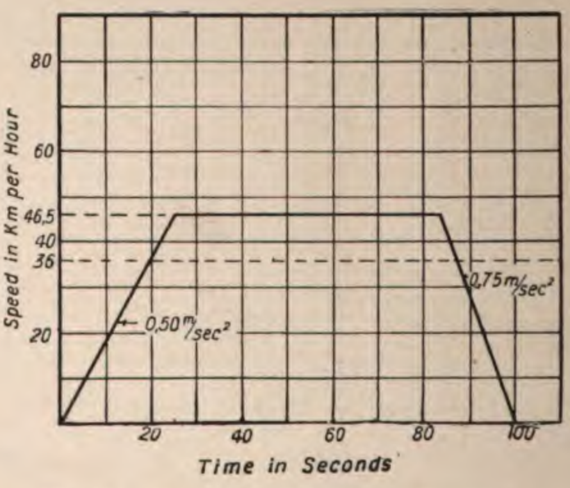


Fig. 114. SIMPLIFIED SPEED-TIME DIAGRAM.
1 Stop per km. Average Speed 36 km per hour.

sec per sec, and to a deceleration (during braking) of 0,75 m per sec per sec. During the latter part of the accelerating period, the acceleration falls off rapidly. This corresponds (in customary methods of electric traction) to the period commencing when the last section of series resistance has been cut out. This period is described as that of acceleration "on the motor curve." For a study of this subject the reader must consult more specialised treatises.[1]

After completion of acceleration, the power is, for short runs, cut off, and the train coasts or drifts, the speed slowly decreasing owing to friction. At the conclusion of the coasting period, the brakes are applied with such a pressure as to produce the desired rate of deceleration. In the case of Fig. 109, the rate of deceleration is 0,75 m per sec per sec.

In Fig. 112 are drawn a number of alternative speed-time curves of the same type and corresponding to the same average speed (36 km per hour) for a 1 km run from start to stop. It will be observed that the lower the rate of acceleration and of deceleration, the higher must be the maximum speed for a required average speed.

In the curve in Fig. 113 a further modification is introduced. This consists in replacing the "coasting" period by a period during which constant speed is maintained by suitable control of the motoı power.

In Fig. 114 the variable accelerating rate is replaced by a constant rate giving the same mean acceleration.[2] Our speed-time diagram is now reduced to three straight lines.

[1] See pp. 32, 62 and 66 of "Electric Railway Engineering" (Parshall and Hobart).

[2] The constant accelerating rate in Fig. 114, which is to be the mean value of the variable accelerating rate in Fig. 113, is best obtained graphically in the following manner:

From the velocity curve in Fig. 115, an acceleration curve is plotted by taking a number of ordinates between $t = o$ and $t = x$, (x = time in seconds at which maximum velocity is attained) and plotting the rate of increase in velocity at any ordinate. The mean height of this acceleration curve gives the mean acceleration in km per hour per sec during the period of acceleration.

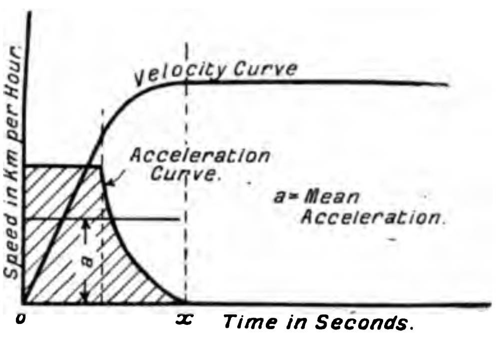


Fig. 115. Graphical Determination of the Value of the Mean Acceleration from the Speed-time Curve.

The straight line velocity

In Fig. 116 the rates of acceleration and deceleration are taken equal and of a value corresponding to the mean of the two rates employed in Fig. 114. This diagram may be regarded as a tolerably fair substitute for the diagram in Fig. 109, and is of a type more amenable to the purposes of extensive preliminary calculations.

In Fig. 117 are given a number of diagrams of the type of Fig. 116, and all corresponding to the same conditions as regards average speed and length of run, but with various accelerating

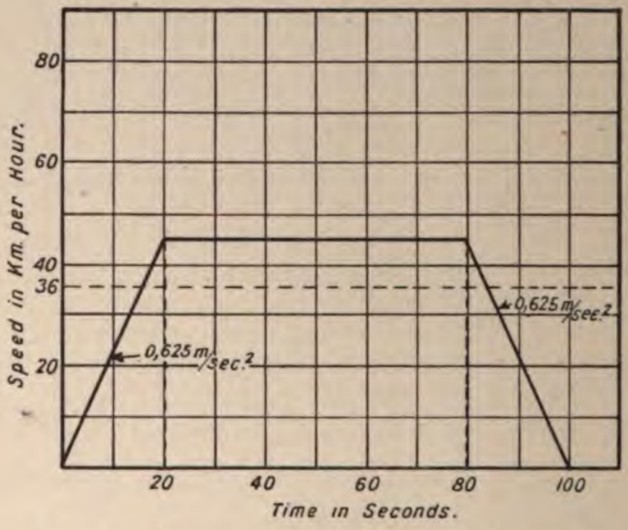


Fig. 116. SIMPLEST FORM OF SPEED-TIME DIAGRAM.
1 Stop per km. Average Speed = 36 km per hour.

rates and, consequently, various maximum speeds. We see that the minimum accelerating rate permitting of attaining the average speed of 36 km per hour with one stop per km is 0,40 m per sec per sec, and that this corresponds to a maximum speed of 72 km per hour, *i.e.*, to a maximum speed equal to twice the average speed.

Tractive Resistance at Constant Speed.—Although the tractive

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curve corresponding to this acceleration must now be drawn in, and using the same velocity curve as before for the breaking period; the uniform maximum velocity line must be put in at such a value that the area of the curve, and consequently the average velocity over the whole period, is the same as before.

resistance is a quantity which varies considerably with the type and condition of the rail, the velocity of the wind, the contour of the train and its mechanical design, and with the character of the permanent way, the rough mean values which have been experimentally obtained are sufficient in calculating the energy consumptions for short runs, without introducing any considerable error into the results. This is owing to the circumstance that for short runs—say up to 3 km—at fairly high average speeds, the energy consumed during the accelerating interval is so large a

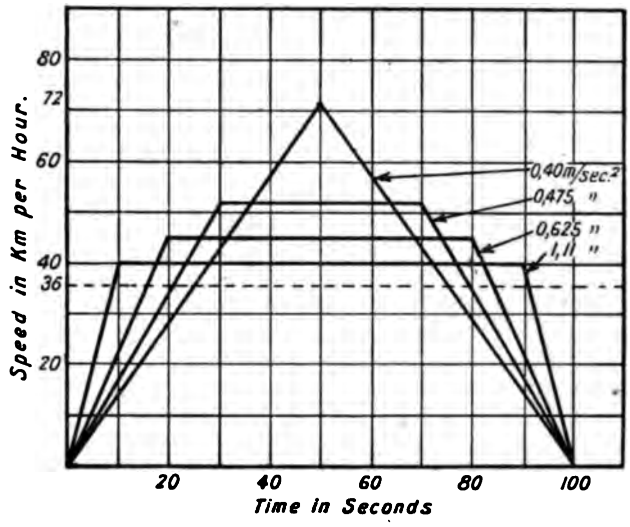


Fig. 117. SIMPLIFIED SPEED-TIME DIAGRAMS FOR DIFFERENT RATES OF ACCELERATION.

percentage of the total energy consumption, that considerable inaccuracy in the data of tractive resistance at constant speed affects the accuracy of the result to but a very small degree. The tractive resistance at starting is very variable, ranging from 7 to 14 kg per ton.

On the Central London Railway the starting resistance was, on the occasion of certain special tests, ascertained to be some 9 kg per ton for a 113-ton train of seven cars. The exceptionally high value of 18 kg per ton has been observed on the City and South London Railway for a 26-ton train.

For speeds ranging from 16 to 160 km per hour Aspinall gives

the following formula for obtaining the tractive resistance at constant speed

$$R = 1{,}12 + \frac{V^{\frac{5}{3}}}{250 + 0{,}45\ L}$$

where R = tractive resistance in kilograms per ton
V = speed in kilometers per hour
L = length of the train in meters.

The curves of Fig. 118 have been plotted, by means of this formula, for train lengths of 30, 300 and 600 meters. The results obtained

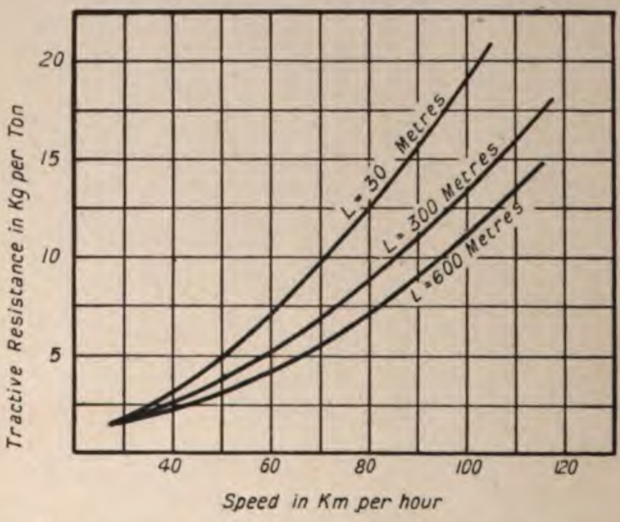


Fig. 118. Curves for Tractive Resistance. (From Aspinall's Formula.)

during the recent high-speed tests at Zossen are shown in Fig. 119, together with the results obtained by Aspinall's formula for the same train length of 23 meters, (in this case, one coach). The weight of the coach was 83 tons.

In tube railways where there is only a small clearance between the tunnel walls and the train the tractive resistance is increased, as is shown by the following curves based on the results of tests.

In Fig. 120, curve A gives the tractive resistance for speeds up to 45 km per hour for a 26-ton train on the Central London Tube Railway, and curve B for a 130-ton train on the same railway. The internal diameter of the tube is 3,5 meters, and the minimum

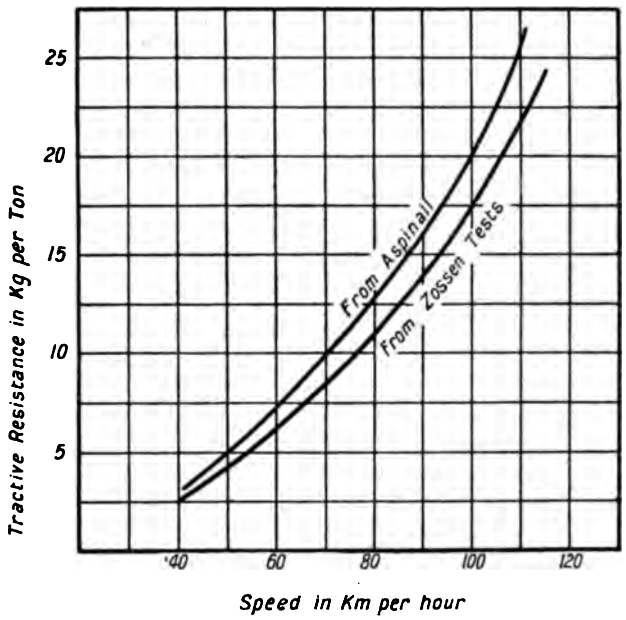


Fig. 119. Curves for Tractive Resistance. (From Zossen Tests.)

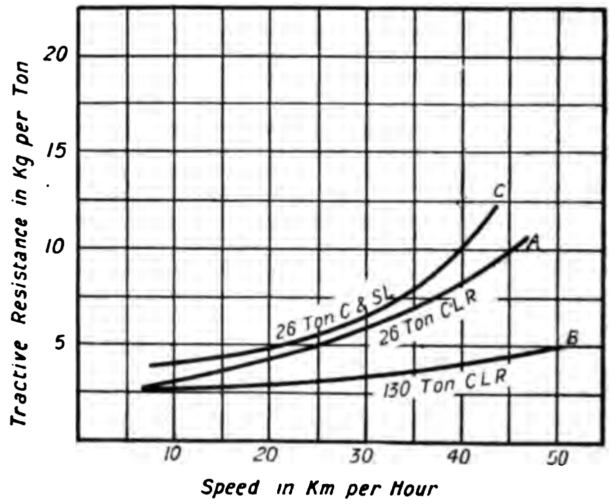


Fig 120. Tractive Resistance on Tube Railways.

clearance between tube wall and train is about 15 cm. Curve C is for a 26-ton train on the City and South London Railway.

From curves A and B an equation has been deduced in which there is a constant figure of 2,70 kg per ton, relating chiefly to

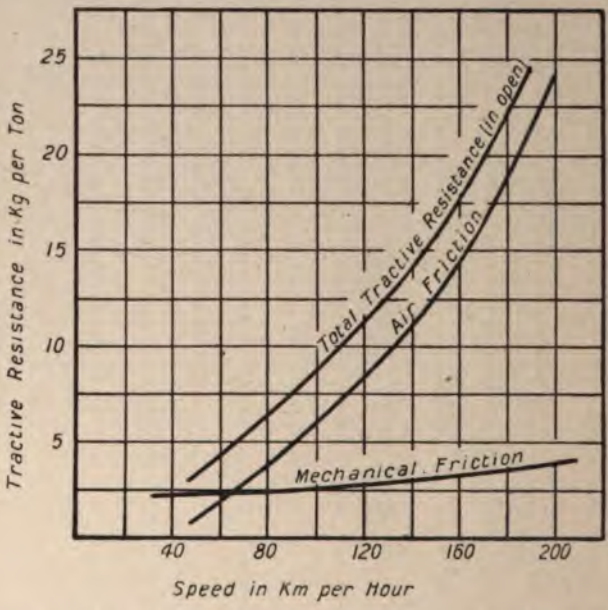


Fig. 121. Analysis of Tractive Resistance. (From Zossen Tests.)

mechanical friction, and also a term depending upon the speed and the weight of the train.

Thus $$R = 2{,}70 + 0{,}09\,\frac{V^2}{W}$$

where R = tractive resistance in kilograms per ton
V = speed in kilometers per hour
W = weight of the train in tons.

The trials at Zossen have shown that at 65 km per hour, the air resistance and the mechanical resistance are about equal, and at 160 km per hour the air resistance is about four times the mechanical resistance.

The values obtained at Zossen are given by the curves in Fig. 121. Aspinall's tests indicated that the air resistance would not equal the mechanical resistances until a speed of 130 km per hour had been reached. In these tests, however, the resistances

measured were those of the coaches hauled by the engine, which latter shielded the coaches to a certain extent and obscured the effect of air resistance.

Although the length as well as the weight of a train should be taken into consideration in estimating the tractive resistance, as is done in Aspinall's formula, yet it is generally more convenient, in practice, to estimate the tractive resistance from curves such as those given in Fig. 122, where the weight only is taken into

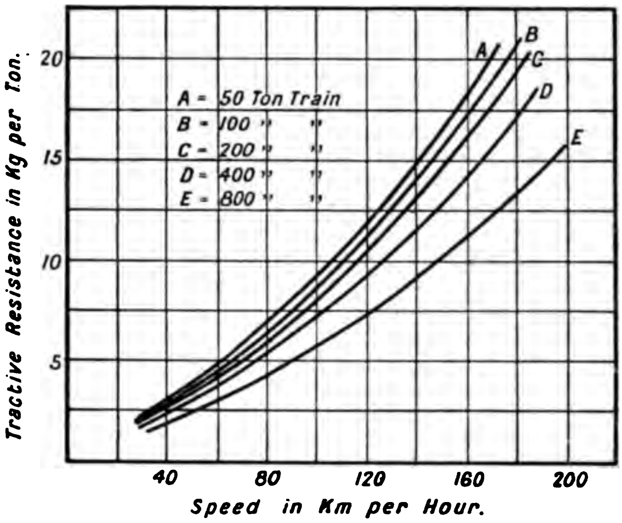


Fig. 122. TRACTIVE RESISTANCE CURVES FOR DIFFERENT WEIGHTS OF TRAINS.

consideration, and, if used with judgment, sufficient accuracy may be obtained with these more convenient curves.

Table LXXXVI. gives for a number of railways certain particulars of weight of train, length of train, etc., and shows that, with the exception of the abnormal experimental rolling stock at Zoss- weight per meter of train length does not vary very consi so that the curves in Fig. 122 would give very much results as the curves in Fig. 118, where the length, and weight of the train, is the criterion taken. Goods tra form an exception to any such approximate conclusion.

The curves for train resistance in tubes, given in only for speeds up to some 40 km per hour. For

train resistance at higher speeds, we must rely on a suitable formula, as no test results are available. Let us consider what form such a formula will have.

There will be, as in the case of a train in the open, a constant figure relating chiefly to the mechanical resistance per ton, and a

TABLE LXXXVI.

Rolling Stock Data.

	Name of Railway.		Number of Seats.	Overall Length in Meters.	Weight in tons exclusive of Passengers.	Tons per Meter.	Seats per Meter.	Seats per Ton.
Motor Cars.	Central London Rly.	cont. curr.	40	14	25	1,8	2,85	1,6
	Metropolitan Rly.	,, ,,	49	16	37	2,3	3,1	1,33
	Metropolitan District Rly.	,, ,,	48	15	24	1,6	3,2	2,0
	Waterloo & City Rly.	,, ,,	50	14,3	—	—	3,5	—
	Great Northern & City Rly.	,, ,,	54	15,3	—	—	3,5	—
	Zossen Car (Siemens & Halske)		48	23	74	3,2	2,1	0,65
	,, ,, (A. E. G.)		48	22	90	4,1	2,2	0,54
	Burgdorf Thun. (3-phase)		66	15	32	2,1	4,4	2,1
Trailer Cars.	Central London Rly.	cont. curr.	48	14	13,4	0,96	3,4	3,6
	Metropolitan Rly.	,, ,,	56	16	17,0	1,06	3,5	3,3
	Metropolitan District Rly.	,, ,,	48	15	16,5	1,1	3,2	2,9
	Waterloo & City Rly.	,, ,,	54	10,6	—	—	5,1	—
	Great Northern & City Rly.	,, ,,	56	15,3	—	—	3,65	—
	City & South London Rly.	,, ,,	32	9,5	7,0	0,74	3,4	4,6
Complete Trains.	Central London Rly.	(7 car train)	324	100	112	1,12	3,24	2,9
	Metropolitan Rly.	(6 car train)	322	98	144	1,47	3,3	2,24
	Met. District Rly.	(7 car train)	328	105	139	1,32	3,1	2,36
	Waterloo & City Rly.	(4 car train)	208	50	59	1,18	4,2	3,5
	Great Northern & City Rly.	(7 car train)	422	108	168	1,55	3,9	2,5
	City & South London Rly.	(4 cars & loco)	128	43	33	0,77	3,0	3,9
	Manhatten Elevated Rly.	(CC 6 car train)	286	86	107	1,25	3,3	2,7
	Mersey Rly.	(CC motor car train)	292	92	120	1,30	3,18	2,42

figure (depending chiefly on the speed) for the air resistance per ton of train.

The air resistance will increase at least as rapidly as with the square of the velocity, quite possibly as the cube, as the air being confined in front of and behind the train, and the clearance being only 15 to 30 cm between train and tube w[illegible] [illegible]re will be a

column of air sucked along with the train and a column of air pushed before it, the resistance offered being dependent on the length of the tube and the means of inlet and outlet of air.

The author proposes the following formula as applicable to the ordinary designs of tube railways and trains:—

$$R = 3 + 0{,}3 \frac{V^2}{W}$$

R = tractive resistance in kg per ton
W = weight of train in tons
V = speed in km per hour

In Fig. 123 the tractive resistance at constant speed in kilograms

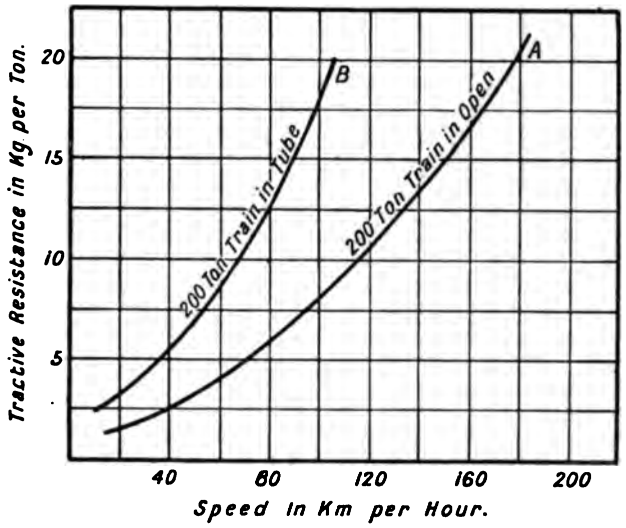


Fig. 123. Author's Curves for Tractive Resistance for a 200 Ton Train in Tube and in Open.

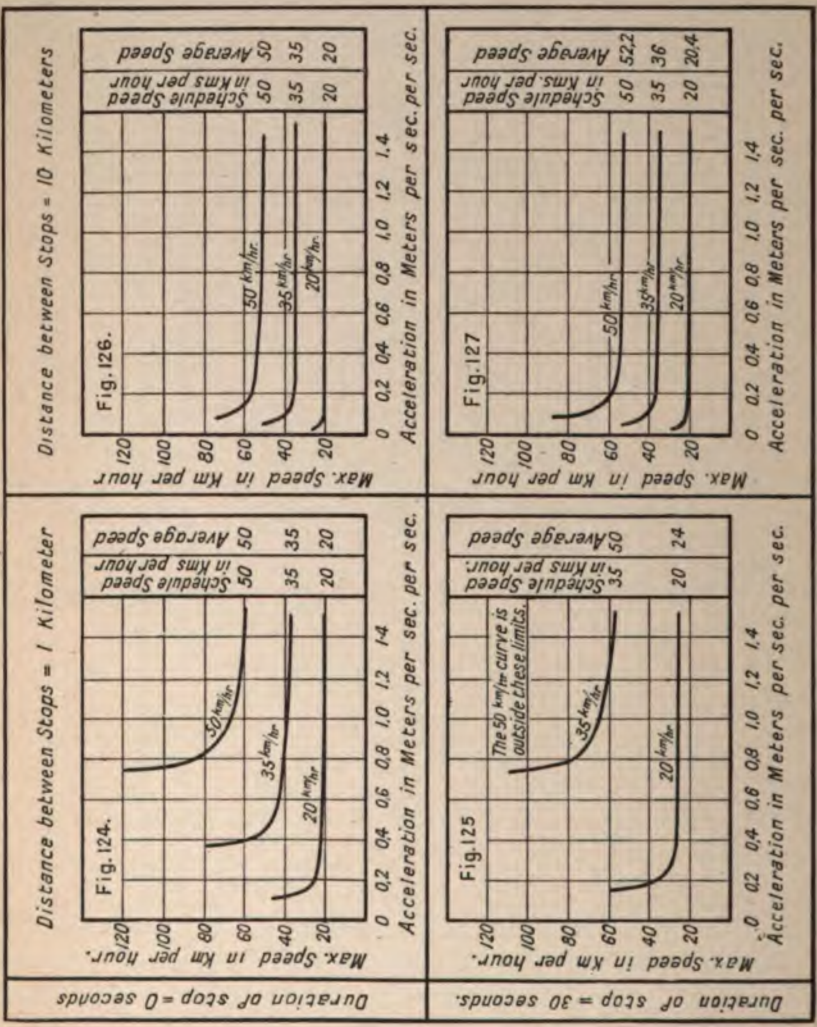
per ton is plotted as a function of the speed in km per hour for a 200 ton train. The lower curve A gives the tractive resistance per ton when the train is travelling in the open (this curve is the same as C in Fig. 122).

The upper curve B gives the probable tractive resistance if the train were in a tube, and is plotted from the formula proposed above.

Although curves plotted to give the tractive resistance in kilograms per ton at various speeds are in the form generally most convenient to the engineer, sight should nevertheless not be lost of the fact

that the more instructive way of considering these questions is to employ the coefficient of friction.

From Fig. 122 we see that a 200 ton train on a well built level



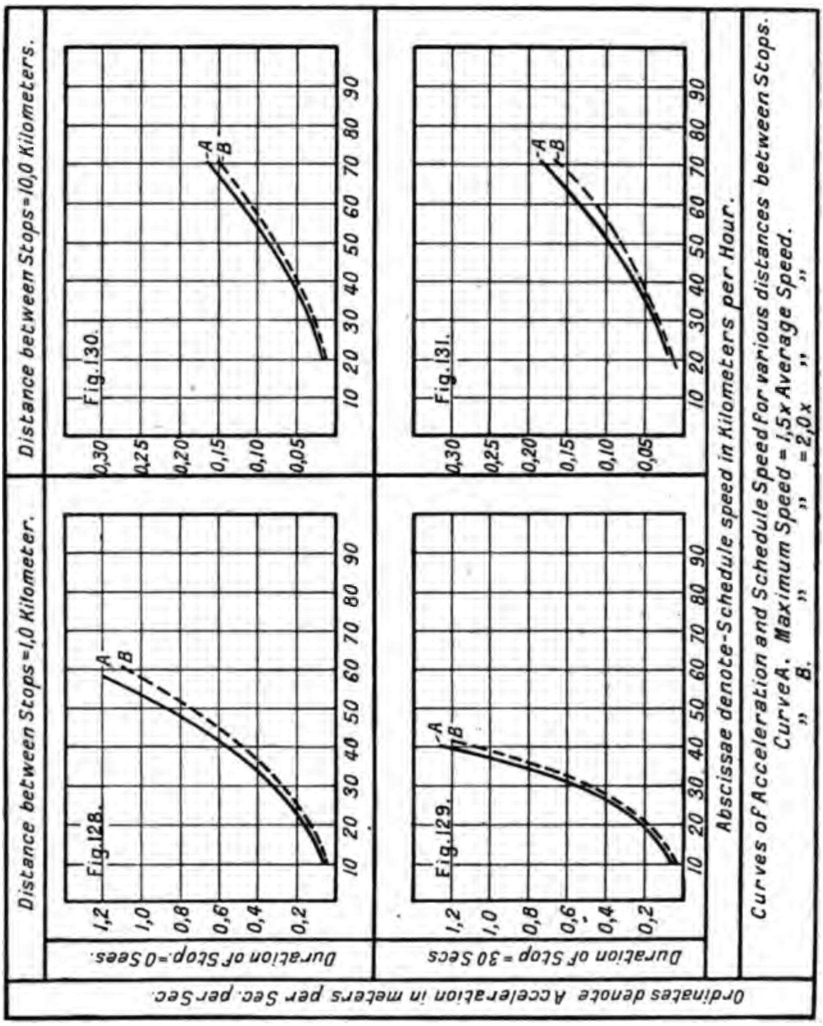
Figs. 124—127. Maximum Speeds necessary in order to obtain certain Schedule Speeds with various Rates of Acceleration.

track requires, at a speed of 100 km per hour, a tractive force of 8 kg (*i.e.*, of 0,008 ton) per ton weight of train.

In other words, a force equal to 0,008 of the force necessary to

raise the train vertically against gravity is required to move it at this speed on a well built level track.

Thus the friction coefficient is 0,008. Coefficients of sliding



Figs. 128—131. RATES OF ACCELERATION NECESSARY TO OBTAIN CERTAIN SCHEDULE SPEEDS.

friction between smooth non-lubricated metallic surfaces are of the nature of 50 to 100 or more times as great, the value depending on the particular metals, on the contact pressure, on the smoothness

of the surfaces in contact, and on other conditions. The coefficient of sliding friction of dynamo brushes on commutators running at peripheral speeds of these same orders of magnitude is some 0,2 to 0,3, depending largely on whether the brushes are copper (0,2), graphite (0,2 to 0,3) or carbon (0,3), and on the particular grades of these materials and on the brush construction.

Number of Stops and Duration of Stop.—The curves in Figs. 124 to 127 show the various maximum speeds required in order to obtain certain values of the *Schedule Speed* for various accelerations. These curves have been worked out for distances of 1 km and 10 km between stops and for duration of stop, of 0 and 30 seconds.

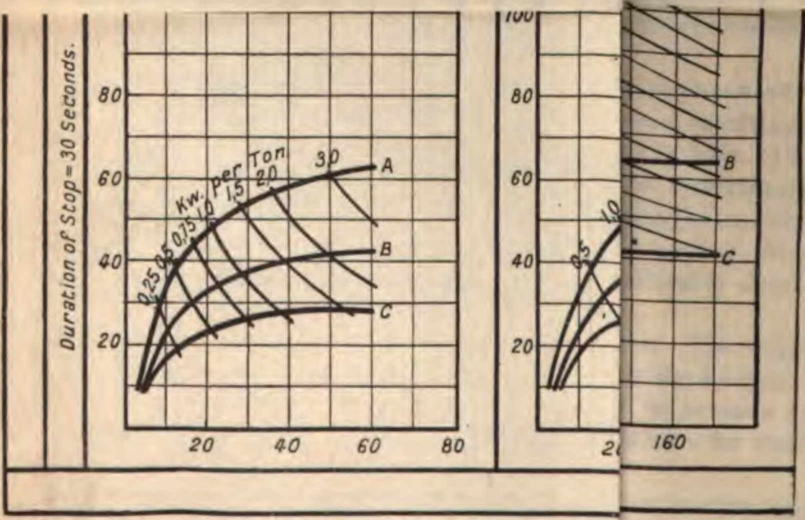
From these curves (which are taken for extreme cases) it is plainly seen that for short runs, the rate of acceleration must be high if a high schedule speed is required, and that, for a long duration of stop, it is impossible to attain a high schedule speed. For long runs, however, a low rate of acceleration is sufficient, and a moderately long duration of stop has but little effect on the required maximum speed.

In Figs. 128 to 131 are plotted curves (corresponding to the curves of Figs. 124 to 127), with accelerating rates as ordinates and with schedule speeds as abscissae. In the full line curves the maximum speed is limited to 1,5 × Average Speed, and this is a reasonable limitation. As a matter of interest, however, the dotted line curves, corresponding to a maximum speed equal to twice the average speed, have been added.

The curves of Figs. 124 to 131 are sufficiently representative of the practical case although obtained by processes involving the assumptions corresponding to the type of diagram in Figs. 116 and 117. In so far as errors are introduced by these approximations they are chiefly of such a nature as to involve a margin on the safe side in making estimates. The processes of carrying through estimates of this nature are discussed in considerable detail in Chapter II. of "Electric Railway Engineering."

Tractive Force with Various Accelerating Rates.—The full line curves in Figs. 132 and 133 show the relation existing between the tractive force in kg per ton of train, to the time in seconds from the instant of starting; the same relation being shown for various rates of acceleration.

The tractive force here plotted is the sum of two tractive forces, the one required to accelerate and the other to maintain the speed against air friction and mechanical friction.



Figs. 134—142. , Curves showing the Watt-hour Ton.

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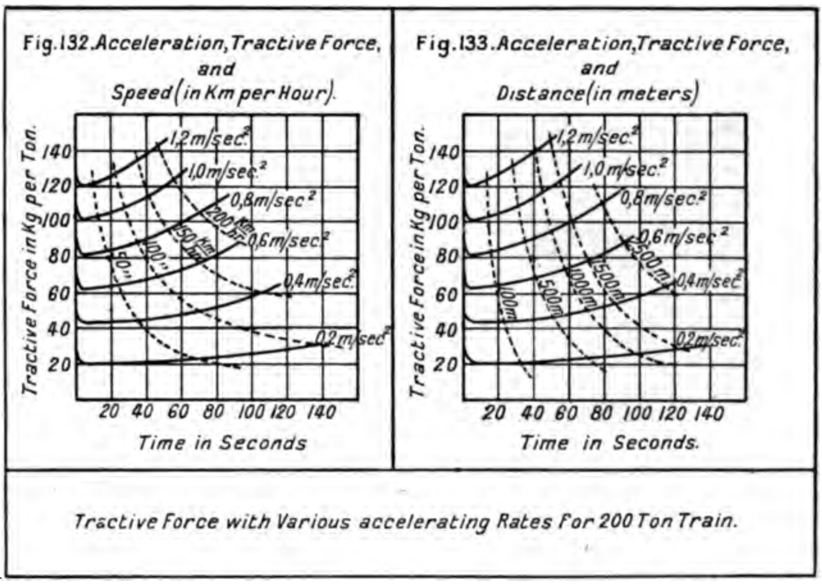
The dotted line curves in Fig. 132 show the speed attained at any time after starting and at any rate of acceleration, curves being put in for 50, 100, 150, and 200 km per hour. The dotted line curves in Fig. 133 show the distance travelled at any time after starting, and at any rate of acceleration, curves being put in for 100, 500, 1000, 1500, 2500 meters.

These curves apply to 200 ton trains, since the frictional resistances are taken to correspond with curve C of Fig. 122, but the frictional resistance is, during acceleration, and especially for high



Figs. 132—133. Tractive Force for Accelerating.

accelerating rates, so small as compared with the inertia resistance, that the data in Figs. 132 and 133 may be used without much error for other train weights.

We now have sufficient data to make rough estimates of the energy consumed at the train axles in operating trains on a level track at given schedules. The results are set forth in the full line curves of Figs. 134 to 142.

To explain the process let us take the case of a run of 1 km from start to stop, at a schedule speed of 20 km per hour and with a stop of 30 seconds duration. Let the accelerating and braking rates be 0,8 meters per second per second.

Collecting together the conditions we have,

Distance between stops ... ... 1 kilometer
Schedule speed ... ... 20 kilometers per hour
Accelerating and braking rates ... 0,8 meters per sec per sec
Duration of stop ... ... 30 seconds.

Total time occupied by the journey (including 1 stop of 30 secs)

$$= \frac{3600}{20} = 180 \text{ secs.}$$

Time occupied by journey (excluding stop) = 180 — 30 = 150 secs.

Average speed attained

$$= \frac{180}{150} \times 20 = 24 \text{ km per hour.}$$

Time of accelerating and retarding periods = 8,8 secs.

Maximum speed attained = 8,8 × 0,8 = 7,05 meters per second
= 7,05 × 3,6 = 25,4 km per hour

Average speed during accelerating period

$$= \frac{25,4}{2} = 13 \text{ km per hour}$$

Tractive force per ton for accelerating (from Fig. 132)
= 83 kg.

Distance covered during acceleration =

$$(8,8)^2 \times \frac{0,8}{2} = 31 \text{ meters}$$

Work performed during accelerating period

$$= 83 \times 31 = 2570 \text{ meter kilograms}$$

$$= \frac{2570}{367} = 7 \text{ watt-hours.}$$

Tractive force per ton at constant speed
(from curve C, Fig. 122) = 1,7 kg.

Distance covered at constant speed

$$= 1000 - 62 = 938 \text{ meters.}$$

Work performed at constant speed

$$= \frac{938 \times 1,7}{367} = 4,3 \text{ watt-hours}$$

Total work performed during the whole journey

$$= 7 + 4,3 = 11,3 \text{ watt-hours.}$$

The groups of curves in Figs. 134 to 142 have been plotted from the results of similar calculations for the various conditions. From this chart we may obtain, for any given distance between stops, any given duration of stop, any given schedule speed and

PLATE XIII.

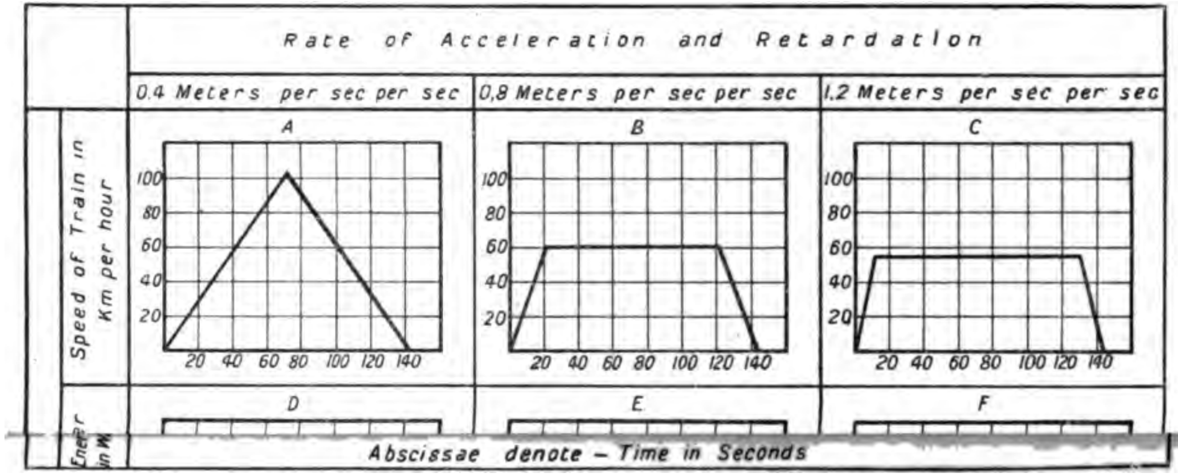


Fig. 143. SPEED, TRACTIVE FORCE, POWER AND ENERGY AT AXLES FOR A 200-TON TRAIN OPERATED AT AVERAGE SPEED OF 51 KW PER HOUR DISTANCE OF 2 KM BETWEEN STOPS.

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any given accelerating rate, the corresponding energy consumption at the axles in watt-hours per ton-kilometer and the

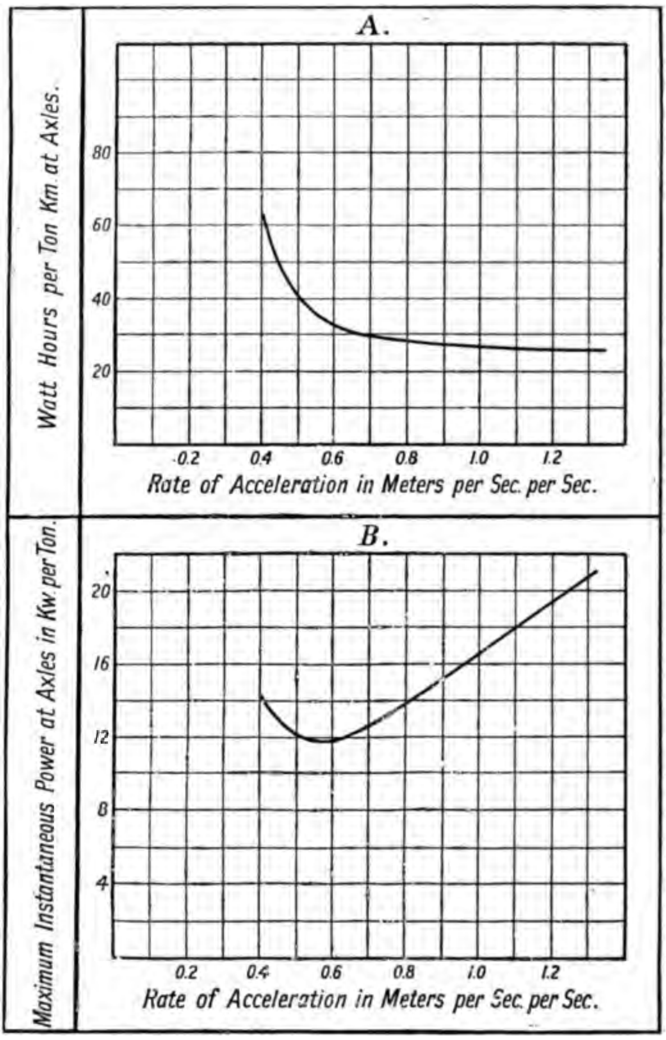


Fig. 144. ENERGY EXPENDED AT AXLES AND MAXIMUM INSTANTANEOUS POWER FOR DIFFERENT RATES OF ACCELERATION. AVERAGE SPEED = 51 KM PER HOUR. LENGTH OF RUN = 2 KM.

orresponding average rate of consumption of energy at the axles, ilowatts.

From calculations similar to the above, Fig. 143 has been prepared. This shows graphically the various steps in the calculations for estimating the energy consumption at the axles. As in all the other figures the case of a 200-ton train is taken, and the calculations are made for the particular case of a 2 km run, with an average speed of 51 km per hour; the energy consumption being shown for three different values of the rate of acceleration. The first important point to be noticed is that at a certain rate of acceleration the *maximum* instantaneous kw input to the axles is a minimum.

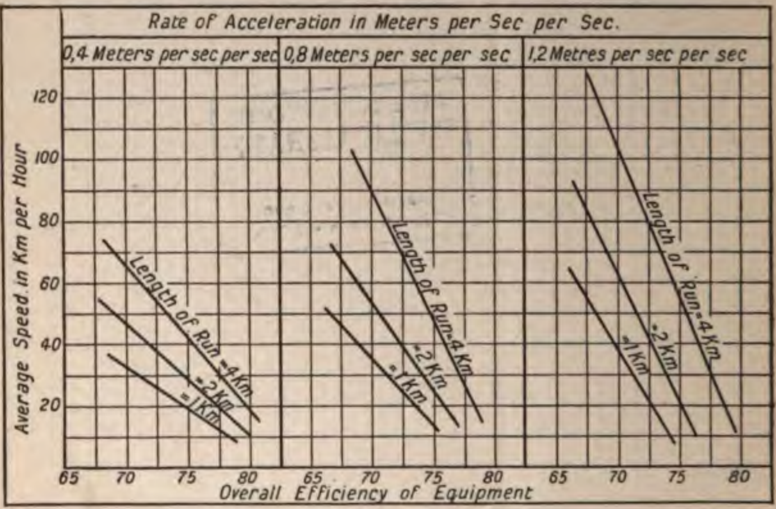
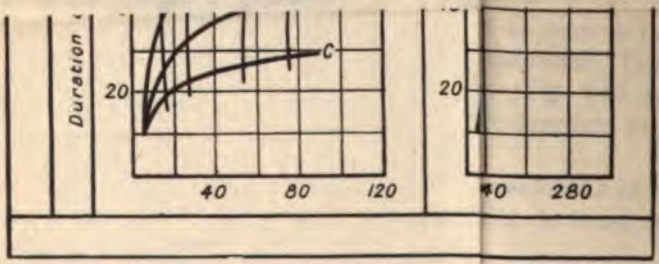


Fig. 145. Curves giving the Overall Efficiency of Equipment.

From Fig. 144 (B) this rate of acceleration is seen to be about 0,6 m per sec per sec for the particular case considered. The *energy* consumption at the axles for the whole run (Fig. 143 (M—O)), however, decreases with increasing rate of acceleration, as is seen from Fig. 144 (A).

Both these figures were plotted from the values shown in Fig. 143 and from values obtained by calculations similar to those used for Fig. 143.

The next step is to estimate the energy input to the trolley, that is, the total energy supplied to the train, including the useful energy (that given up to the axles), the energy lost in the motors and gearing, and the energy lost in the controlling rheostats.



Figs. 146—154. CURVE SHOWING THE WATT-L EFFICIENCY OF

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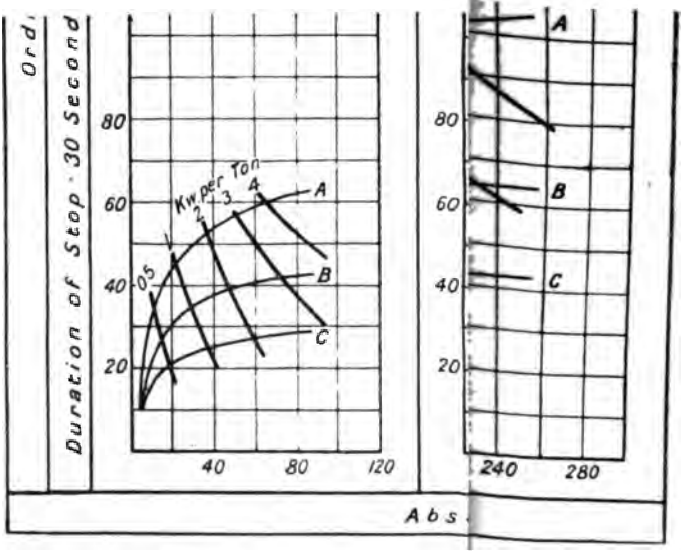

Figs. 155—163. CURVES SHOWING THE AVE TROLLEY PER TON

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The ratio of the energy given up to the axles (Figs. 134—142) to this total energy supplied is the overall efficiency of the equipment.

The efficiency of the motors at their *average* load (including gearing) can be taken as 85 per cent. for a continuous current motor equipment suitable for a 200 ton train. That this is a reasonable value is readily seen by referring to the efficiency curves of modern continuous current railway motors.

The overall efficiency of the equipment, however, is considerably lower, on account of the energy lost in the rheostats during the acceleration period. The chief factors which determine the value of the rheostat loss are the length of the acceleration period and the maximum velocity required.

The curves in Fig. 145 show the overall efficiency of equipment plotted as a function of the average speed. The values from which these curves were plotted are representative of present practice with continuous current equipments. They are necessarily only approximate. Curves are shown for various lengths of run and for various rates of acceleration. As would be expected, the efficiency is higher the longer the run (as the necessary *maximum* speed for any given *average* speed will be less). The efficiency is also higher, the lower the average speed required.

Applying these efficiency curves to the curves of Figs. 134—142 (for input to the axles), the curves in Figs. 146—154 are obtained, which gives the input to the trolley. The overall efficiencies are shown plotted in fine lines across the input curves.

The "energy input to the trolley" curves are again reproduced in Figs. 155—163, and the average kw input to the trolley is shown by the thick lines across these curves.

The above curves are deduced from considerations of continuous current equipments, but the total energy consumption curves (Figs. 146—163) may be used for single phase equipments, as, although the average efficiency of the motors is less, this is largely or entirely offset by the fact that there is no rheostat loss, the loss in the transformers being comparatively small.

The more exact and exceedingly laborious methods of calculating from the precise characteristic curves of the motor employed in each individual case are described in Chapter IV. of "Electric Railway Engineering."

CHAPTER XI

TRACTION MOTORS AND THE ELECTRIFICATION OF RAILWAYS

A. Traction Motors.

Introduction.—The train consumption in watt hours per ton km is, as stated at the conclusion of the preceding chapter, sufficiently independent of the particular system of electric traction adopted in various cases to justify the general employment of the values in Figs. 146 to 154, for 200-ton passenger trains, in all cases where the permanent way and rolling stock are of modern construction. From this point onwards, however, there must be taken into account in the calculations a number of conditions with respect to which the particular system employed exercises a considerable influence.

No one who has followed electric traction developments during recent years can have failed to note the wide difference in the individual capacities of the motors which are becoming customary in the three leading systems. Instances of three phase railway motors with a rated capacity of 1500 hp each[1] are now available; whereas the rated capacity of the largest continuous current railway motors is not over 550 hp. As to single phase railway motors, it is becoming quite evident that 200 hp per motor is the highest rating which, in the present state of engineering knowledge, can be considered advisable. Indeed, Reichel in March, 1907,[2] expressed the opinion that for single phase railway motors, "a one-hour capacity of 180 hp per single motor is, in general, to be regarded as the extreme limit, *if no special means for artificial cooling by air circulation are provided.*" Reichel further points out that "it is not a simple matter to suitably provide for the introduction of

[1] See p. 277 of *Electrical Engineering* for February 20, 1908.

[2] "Eine Stundenleistung von 180 P.S. für den einzelnen Motor ist im allgemeinen als äussere Grenze anzusehen, wenn keine besondere künstliche Kühlung mit Frischluft stattfindet. Die Zuführung der Luft ist bei Motorwagen nicht leicht, und daher ist es besser, ohne solche auszukommen." "Zeitschrift Vereines Deutscher Ingenieure," vol. 51, p. 1027.

air into the motor in the case of motor carriages, and hence it is preferable to dispense with forced draft."

The 550 hp continuous current motors of the New York Central locomotives are not of the enclosed type. Enclosed continuous current railway motors of rated capacities of 400 hp each will, however, be no heavier than 200 hp single phase railway motors, assuming equal armature speeds at rated load in the two cases. In equipments for motor carriages, the *upper limits* should preferably be taken at 150 hp for single phase, 300 hp for continuous current, and 400 hp for three phase. For customary purposes the *most suitable* sizes for equipments for motor carriages will generally be found to be 150 hp, 200 hp and 250 hp in the three cases.

In an article in the *Railway Gazette* for May 10th, 1907, the present author has indicated the misleading nature of the data which has been put forward by the advocates of single phase railways. It may not be amiss to point out here a few instances.

(1) On p. 270 of vol. 36 of the *Journal of the Inst. of Elec. Engrs.*, Schoepf states that "the Westinghouse single phase motor of 150 hp capacity weighs 2,46 tons, and a similar continuous current motor of equal capacity weighs 2,52 tons, which proportion is practically the same throughout the range of Westinghouse traction motors." This works out at 16 kg per hp. In the *Times Engineering Supplement* for April 17th, Kelly quotes the weight of the 150 hp Westinghouse single phase motor as 2,72 tons, which is 18 kg per hp. Kelly on this occasion makes the following statement: "The most enthusiastic advocates of the single phase system have never claimed that the motor was as light in weight or as low in first cost as the present 600-volt continuous current motor." Kelly is now chief of the department conducted up to a couple of years ago by Schoepf, and yet we have Schoepf asserting that the single phase motor is lighter than the continuous current motor and Kelly asserting that it is considerably heavier. Both Schoepf and Kelly are advocates of the single phase system. On p. 683 of *Electrische Bahnen und Betriebe* for December 14th, 1906, the weight of a Westinghouse 100 hp single phase motor is given as 2,36 tons; this is 23 kg per hp. Thus we have for Westinghouse motors of about the same rated capacity 16, 18 and 23 kg stated to be the weight per hp.

(2) In a letter published in the *Times Engineering Supplement*

for November 22nd, 1905, Eichberg states that "Excepting the power transformer, the weight of the alternating current equipment is practically the same as that of the continuous current for the same working conditions. But, owing to the use of a power transformer, the total weight per car will be increased by about 2 per cent. for the normal city service." On p. 486 of the *Railway Gazette* for May 24th, 1907, Dalziel states that: "As regards weights, these are not of supreme importance in railway work, but taking the actual practical weights of single phase motors, as applied to vehicles, without any academic discussion as to whether forced ventilation has or has not been applied to continuous current motors, or could, or could not be, it may be stated at once that motor for motor, on present designs, the weights are about equal. The transformer makes the equipments, as a whole, heavier than continuous current, but as it confers the advantage of perfectly flexible and efficient speed control, besides reducing the pressures of all the working parts to a low value, reliable in working and safe to attend to and manipulate, it is worth its carriage."

(3) Dawson has stated (p. 264 of Vol. XXXVI. of the *Journ. Inst. Elec. Engrs.*) that "the weight of a 150 hp continuous current motor, rated on the 1 hour 75° C basis, is 2,7 tons, and the weight of a 115 hp single phase motor rated exactly on the same basis is 2,4 tons. If we take the weights of two motor trucks, one set equipped with four 150 hp continuous current motors, the other with four 115 hp single phase motors—that is, simply the complete motor trucks—we find that the weight of the continuous current motor equipment would be nearly 26 tons as against 27 tons for the single phase equipment." Dawson passes over the fact, however, that he is comparing an aggregate of 600 hp of continuous current motors with an aggregate of only 460 hp of single phase motors. Furthermore, the heaviest trucks employed under motor coaches equipped with *continuous current* motors do not exceed 5,5 tons each in weight, or 11 tons per pair of trucks, and even the 240 hp G E 69 motor weighs with gear and gear case only about 2,75 tons, or 11 tons for four motors. Thus a pair of trucks equipped with four G E 69 motors, *i.e.*, with an aggregate of **960 hp** of motors, will weigh only 22 tons. The 26 tons stated by Dawson to be the weight of two trucks carrying **600 hp** of continuous current motors is altogether unreasonable. A pair of trucks carrying four 125 hp G E 66 motors, *i.e.*, an aggregate of 500 hp of continuous current motors, weighs only 18,5 tons. If Dawson's

figure of 27 tons is correct for the weight of a pair of trucks carrying an aggregate of only 460 hp of single phase motors, he has certainly not made a point for the single phase system.

Ample material is available for concluding that the weight of an *unventilated* and correctly rated 150 hp 25 cycle single phase motor is, at the present stage of development, not less than some 26 kg per hp for an armature speed of 500 rpm at rated load. This is when rated on the basis that at the end of one hour during which it has been carrying its rated load, the thermometrically determined temperature rise of the hottest accessible interior part is 75° C. We have ample data for knowing that the weight of the corresponding *unventilated* continuous current motor designed in the light of modern practice, and for the same speed at its rated load, is some 13 kg per hp. In both these cases the weights are exclusive of gear and gear case. To allow for gear and gear case, some 15 per cent. may be added to the weight for continuous current and some 8 per cent. for single phase motors.

The One Hour Rating.—The maximum output which a traction motor is called upon to develop is several times greater than its average output during the time in which it is in service; but this maximum output is only required for a few seconds, and usually only at periodic intervals of a few minutes. The average output of the motor is too low a figure, however, to serve as a basis for the rating of traction motors, and also gives little idea of the maximum output required of the motor. The empirical basis of a one hour constant output sufficient to cause a maximum temperature rise of 75° C at the end of this hour has been widely accepted as the basis upon which to rate traction motors. The value of this one hour rating will be dependent on the following properties of the motor:—

(1) The efficiency of the motor without gear;

(2) The weight of the motor without gear;

(3) The provisions for ventilation.

Let us consider the influence of these three factors upon the rated output of the motor.

(1) *The Efficiency.*—The energy, represented by the internal losses of the motor, is expended in heating the material of the motor. Neglecting the loss of heat by radiation and conduction to the circulating air, the rise in temperature is directly proportional to the value of the internal loss.

(2) *The Weight.*—Under the conditions as above stated, the average temperature rise will, for a given value of the internal loss,

be inversely proportional to the weight of the motor. A large motor will require more heat energy to raise it to a given temperature than will be required in the case of a small motor. The consequence of this as regards the ratio of the one hour rating to the service capacity is discussed in the section at the foot of this page, entitled "The Service Capacity."

(3) *The Ventilation.*—Ventilation enables more energy to be expended in the motor without overheating it, since much of the heat will be conducted away by the circulating air. It is preferable to give the motors natural ventilation only, *i.e.*, to limit the openings in the case to very small apertures. The armature core should, however, be provided with ducts, in order that there may be a circulation of air through all internal parts of the motor. Apertures in the casings of the motors are only allowed when there is no danger of mud or water entering the motor, and, in general, a *totally* enclosed motor is to be preferred. Single phase motors, however, and in a few cases continuous current motors, are, in the more recent designs, often provided with an artificial circulation of air by forced draught, the natural circulation due to the armature being reinforced by a draught of air through the motor from a fan equipment.

The Service Capacity.—The one hour rating, although the only basis of rating which is sufficiently simple to permit of comprehensive comparisons, is nevertheless by no means a satisfactory criterion of the service capacity of a motor when installed on locomotives or cars and running under actual service conditions. While service capacity depends but slightly on the weight, it is very dependent upon the ventilation facilities provided for carrying away the heat developed in the motor as a consequence of the iron and copper losses in it. Of two motors which rate equally on the one hour basis and are equally ventilated, the lighter will have the greater *service* capacity. For this reason the service capacity of motors of totally distinct type cannot be deduced from a comparison of their one hour ratings. The latter is only quantitatively useful in establishing comparisons between motors of the same type. Thus, if the single phase equipments would do as much per ton *in service* as continuous current equipments, the fact that they rate lower on the one hour basis would not even be worth mention. As a matter of fact, however, they are *worse* when compared rigorously on the basis of their *actual service capacity* than when compared on the basis of their *one hour rating*, inasmuch as in the

hour's run the greater part of the heat is used in raising the temperature of the motor, so that the heavier the motor the higher it will rate, whilst in service the temperature becomes steady and all the heat has to be got rid of by ventilation. Since, however, a rigorous comparison on the basis of actual service capacities is so elaborate an undertaking as to preclude arriving at broad conclusions, and since furthermore the single phase motor is favoured by basing the broad comparison on the one hour rating, the latter basis of rating is employed in the following investigation.

A Comparison on the Basis of the One Hour Rating.

The efficiencies at rated output do not vary greatly for the different types of motors, but this comparatively small difference has an appreciable effect on the weight. For every ton of material in a ventilated motor (*i.e.*, in a motor which, while provided with a few small openings, does not have air forced through it) running at, say, 500 rpm, some 4700 watts must be expended in order to occasion, in one hour, a thermometrically determined temperature rise of 75° C above the temperature of the surrounding atmosphere. If the motor is provided with forced draught, some 6600 watts per ton must be expended. With these figures as a basis, let us see what hp output (one hour 75° C) can be obtained from a motor weighing 2,5 tons without gear, and to run at 500 rpm. The output will, of course, be different for the three types on account of the different efficiencies, and so we must deal with each type separately.

(a) *Continuous Current Motor of the Ventilated Type.*—The weight of the motor without gear is 2,5 tons. The total internal loss at rated load will be 4700 × 2,5 = 11 250 watts. A modern continuous current motor of such a size will have an efficiency (without gear), at rated load, of about 93 per cent. Thus the loss of 11 750 watts is some 7,0 per cent. of the total input. Consequently the input in kw =

$$\frac{11\,750 \times 100}{7{,}0 \times 1000} = 168 \text{ kw.}$$

The output in kw to the gear will be 168 × 0,93 = 156 kw. Assuming a gear efficiency of 96 per cent., the output to the axle will be 150 kw. This is the rated output and, expressed in horse power, is equal to 200 hp. The weight is thus 12,5 kg per hp of rated output. We thus see that a 200 hp 500 rpm continuous current motor of the ventilated type will weigh about 2,5 tons.

In order to confirm this conclusion, let us compare these figures

with the ascertained data of two well-known motors, which are designated as G E 69 and G E 66 respectively.

G E 69. Rated output (one hour 75° C) 240 hp.
179 kw.
Efficiency at 240 hp 550 v. . 93,3 per cent. excluding gear.
Gear loss . . . 4,5 per cent. of input.
Efficiency at 240 hp (with gear) 88,8 per cent.

$$\text{Input in kw} = \frac{179}{0{,}888} = 201{,}5 \text{ kw.}$$

Loss in motor (100—93,3) per cent. = ... 6,7 per cent. of input.
= 13,5 kw.
Weight without gear and case 2,51 tons.

$$\text{Watts per ton} = \frac{13\,500}{2{,}51} = 5380 \text{ watts.}$$

G E 66. Rated output . . . 125 hp.
93,3 kw.
Efficiency at 125 hp . 92,8 per cent. including gear.
Gear loss . . . 3,5 per cent. of input.
Efficiency at 125 hp (with gear) . . . . 89,3 per cent. of input.

$$\text{Input in kw} = \frac{93{,}3}{0{,}893} = 104{,}5 \text{ kw.}$$

Loss in motor 100 — 92,8 = 7,2 per cent. of input.
= 7,53 kw.
Weight without gear and case . . . . 1,8 tons.

$$\text{Watts per ton} = \frac{7530}{1{,}8} = 4200 \text{ watts.}$$

(*b*) *Single Phase Motor of the Ventilated Type.*—The weight of the motor without gear, is, as before, taken equal to 2,5 tons. Also, as this weight of material is to be raised to the same temperature as in the case of the continuous current motor, the internal loss must be the same, *i.e.*, 4700 × 2,5 = 11 750 watts. The efficiency (without gear) of a modern single phase motor is not greater than 87 per cent., thus the loss of 11 750 watts is some 13 per cent. of the total input, or the input in kw =

$$\frac{11\,750 \times 100}{13 \times 100} = 90{,}5 \text{ kw.}$$

The output to the gear, in kw, will be 90,5 × 0,87 = 78,5 kw. Assuming a gear efficiency of 96 per cent., as before, the output to the axle will be 75,0 kw. This is the rated output, and, expressed in horse power, is equal to 100 hp. The weight is consequently 25 kg per hp of rated output.

(*c*) *Three Phase Motor of the Ventilated Type.*—As before, the weight of the motor without gear is 2,5 tons. The internal loss, as before, is 4700 × 2,5 = 11 750 watts. The efficiency (without gear) of a modern three phase railway motor of this size may be taken at 94,3 per cent., thus the loss of 11 750 watts is some 5,7 per cent. of the total input, or the input in kw =

$$\frac{11\ 750 \times 100}{5{,}7 \times 100} = 206 \text{ kw.}$$

The output to the gear in kw will be equal to 206 × 0,943 = 194 kw. Again assuming a gear efficiency of 96 per cent., the output to the axle will be 186 kw. This is the rated output, and, expressed in horse power, is equal to 250 hp, or a weight of 10 kg per hp of rated output. These results are brought together in Table LXXXVII.:—

TABLE LXXXVII.

Rated Output of Motors of different Types but of equal Weight and for equal Speed of 500 rpm; Ventilated, but not with forced Draught.

Type of Motor.	Weight of Motor without Gear (Metric Tons).	Assumed efficiency without Gear, at Rated Output.	Assumed efficiency of Gear.	Rated hp on 1 hr 75° C. Basis.	Weight in kg, per hp of Rated Output.
Cont. Curr.	2,5	93,0%	96%	200	12,5
Single phase	2,5	87,0%	96%	100	25,0
Three phase	2,5	94,3%	96%	250	10,0

Thus we find that for motors of equal weight, and for equal ventilating provisions, the continuous current motor will have double the output of the single phase motor. Also, that the three phase motor will have one and a quarter times the output of the continuous current motor.

Let us see whether these results are confirmed by the actual weights and outputs of existing motors. In Table LXXXVIII, the

rated hp, total weights and weights per hp are given for three of the largest and most modern single phase motors, for three modern continuous current motors, and for three three phase motors. The average values of the weight, in kg per hp, are some 17 kg for single phase, 11 kg for continuous current, and 10 kg for three phase. The nine examples in this table were selected, as representing the most modern practice, from the larger Table XC., which includes, besides many other examples of motors, columns setting forth the weight of complete electrical equipment. Our estimated figure for the three phase motor is in correspondence with the average value for existing motors, *i.e.*, some 10 kg per hp. The estimated figure of 12,5 kg per hp for continuous current also corresponds well with the average for existing motors. The most modern continuous current motors are even lighter, occasionally having a weight per hp as low as 10 kg. The estimated figure of 25 kg per hp for single phase motors is much higher than the average of the three set forth in Table LXXXVIII., which is some 17 kg per hp. It must be remembered, however, that the above figure of 25 kg per hp refers to a motor provided only with natural ventilation, whereas the single phase motors taken as examples for Table LXXXVIII. are provided with forced draught. This, together with their higher armature speeds, accounts for the relatively low figure for the weight per hp.

TABLE LXXXVIII.

Data of Representative Railway Motors.

System.	Type of Motor.	Rated hp 1 hour 75° C. Basis.	R.P.M. at Rated Load.	Frequency in Cycles per sec.	Weight of Motor excluding Gearing.—Tons.[1]	Weight per hp, in kg.	Railway on which Motor is in use.[1]
Single phase Alternating	A.E.G. W.E. 51	115	600	25	2,4	20,8	London B. S. Coast Ry.
	Siemens Schuckert	175	700	25	2,77	15,8	Heysham-Morecambe M. Ry.
	Oerlikon	200	650	15	3,38	16,9	Seebach-Wettingen Ry.
Continuous current	G.E. 68	175	—	—	2,15	12,3	Boston Elevated Ry.
	G.E. 69C	232	470	—	2,5	10,8	New York Central Ry.
	G.E. 69B	240	530	—	2,51	10,4	Metropolitan District Ry.
Three phase	Siemens & Halske	250	900	50	3,2	12,8	Marienfeid-Zossen
	Ganz & Co.	300	730	25	2,7	9,0	Tender for Metropolitan
	Ganz & Co.	1500	225	15	13,1	8,7	Simplon and Valtellina

[1] For references see Table XC.

In the published descriptions of single phase motors, it is not always clearly stated in what way the motors are ventilated; thus in one case the 175 hp Siemens Schuckert motor is described as having "artificial ventilation" (Künstliche Kühlung), but whether or not an external blower is provided is not stated. But in another instance (in the Seebach-Wettingen Locomotive) this same motor is cooled with a forced draught.[1] In some cases the information is more definite; thus, referring to the New York, New Haven and Hartford locomotive equipped with four 250 hp Westinghouse single phase motors (see Table XC., No. 8), McHenry, the Vice-President of the N.Y.N.H. & H. Railway, writes thus:—

"The four main traction motors, the high potential transformers and the main circuit rheostats are cooled by air furnished at low pressure by means of two motor-driven centrifugal blowers, which draw air through openings in the cab. The low-pressure air has two paths. One path passes first through the transformer and then to the rheostat. The other path goes directly to the motors. It enters the armature near the shaft, passes around and between the armature laminations, flows outward through the ventilating ducts in the field cores, and reaches the outer air through perforated caps on the frame of the motor. Since a considerable volume of air is required for each motor, and since it is undesirable to cause the air to assume a high velocity, it has been necessary to provide a large flexible conduit between the air passages on the cab and those on the motors proper. The flexible conduit is made of heavy canvas tubing, which is reinforced with wire and given an accordion pleating. By the use of the air blast, the temperature of the motors under load has been so decreased that the continuous rating (200 hp) is nearly equal to the one hour rating (250 hp)."[2]

If we assume that all three types of motor are ventilated with forced draught, then for the same temperature rise, we can expend about 6600 watts per ton instead of 4700 watts. The hp outputs on the 1 hour 75° C basis will now be somewhat different. They will be as follows:—

(*a*) *Continuous Current Motor with Forced Draught.*—The total losses will be 6600 × 2,5 = 16 5C0 watts. Assuming the efficiency to be the same as before, *i.e.*, 93 per cent., the total input will be

$$\frac{16\ 500 \times 100}{7 \times 1000} = 236 \text{ kw.}$$

[1] *Electrical Engineering*, Vol. III., p. 679.
[2] The *Railway Gazette*, August 30, 1907, p. 205.

The output to gear will be 236 × 0,93 = 219 kw. And assuming a gear efficiency of 96 per cent., the output to the axle will be 210 kw, and the rated horse power output will be 280 hp, or a weight of 8,9 kg per hp output.

(*b*) *Single Phase Motor with Forced Draught.*—The total loss will, as in the case of the continuous current motor, amount to 6600 × 2,5 = 16 500 watts. Assuming the efficiency to be, as before, 87 per cent., then the total input will be

$$\frac{16\,500 \times 100}{13 \times 1000} = 127 \text{ kw.}$$

The output to the gear will be 127 × 0,87 = 110,5 kw. And assuming a gear efficiency of 96 per cent., the output to the axle will be 106 kw, or the rated horse power output will be equal to 142 hp, or a weight of 17,6 kg per hp of rated output.

(*c*) *Three Phase Motor with Forced Draught.*—The total loss is 6600 × 2,5 = 16 500 watts. Assuming the same efficiency as in the previous case, *i.e.*, 94,3 per cent., the total input to the motor will be equal to

$$\frac{16\,500 \times 100}{5{,}7 \times 1000} = 290 \text{ kw.}$$

The output to the gear will be 290 × 0,943 = 274 kw. And assuming a gear efficiency of 96 per cent., the output to the axle will be 263 kw, and the rated horse-power output 350 hp, or a weight of 7,15 kg per hp.

Collecting these results in tabular form we have the following :—

TABLE LXXXIX.

Rated Output of Motors of different Types, but of equal Weight, and for equal Speed (namely, 500 rpm) with forced Draught.

Type of Motor.	Weight of Motor without gear (Metric Tons).	Assumed efficiency (without Gear) at Rated Output.	Assumed efficiency of Gear.	Rated hp on 1 hr 75°C. Basis.	Weight in kg per hp of Rated Output.
Continuous current	2,5	93,0%	96%	280	8,9
Single phase	2,5	87,0%	96%	142	17,6
Three phase	2,5	94,3%	96%	350	7,2

The figure given in the above table for the continuous current motor is distinctly lower than any of the figures given in Table LXXXVIII., since these last do not refer to motors provided with forced draught. The figure for the single phase motor, on the other hand, compares very closely with those given in Table LXXXVIII. Thus we have, for a single phase motor, weighing 2,5 tons, and provided with forced draught, a rated output of 142 hp, or a weight of 17,6 kg per hp. The average value in Table LXXXVIII. was 17,0 kg per hp. Let us compare our estimated values of Tables LXXXVII. and LXXXIX. with those given in Table LXXXVIII. Take for example the continuous current motor designated as GE 69 B, and rated (on the 1 hour, 75° C basis) at 240 hp. This motor weighs only 2,51 tons without gear and gear case, or a weight of 10,5 kg per hp. The case of this motor has small openings for providing natural ventilation. The weight per hp decreases slightly with increasing output, and consequently our figure of 12,5 kg per hp, given in Table LXXXVII., compares very favourably. The efficiency (without gear) of this motor is 93,3 per cent. and the efficiency of the gear is 95,8 per cent. As an example of a single phase motor, let us take the Allgemeine Elektricitäts Gesellschaft's W E 51 115 hp motor, which weighs 2,4 tons without gear and gear case, or 20,8 kg per hp. This motor is of the artificially ventilated type, and consequently we must compare the weight per hp with our figure of 17,6 from Table LXXXIX. The efficiency (without gear) of this motor at rated load is 86 per cent., and the efficiency of the gear is about 96,5 per cent.

In Figs. 164 and 165 are drawn to the same scale (1 to 24,4) outline sketches of the G E 69 B and the W E 51. It is evident from the figures that the W E 51 is *actually the larger motor*, although it has only *half the capacity*.

The Siemens-Schuckert series motor, which is rated at 175 hp, has a weight of only 2,77 tons without gear and gear case, or 15,8 kg per hp. This is, however, a larger motor, and runs at a 30 per cent. higher speed than the 2,5-ton motor of Table LXXXIX., which is rated at 142 hp with forced draught. The two motors, the G E 69 B continuous current motor and the Siemens-Schuckert 175 hp single phase commutator motor, are, so far as the author is aware, the lightest for their (1 hour 75° C) output, of the respective types so far as relates

to *authenticated* weights. The three phase motor of the Ganz Co., rated at 300 hp, weighs 2,7 tons, or only 9 kg per hp. This

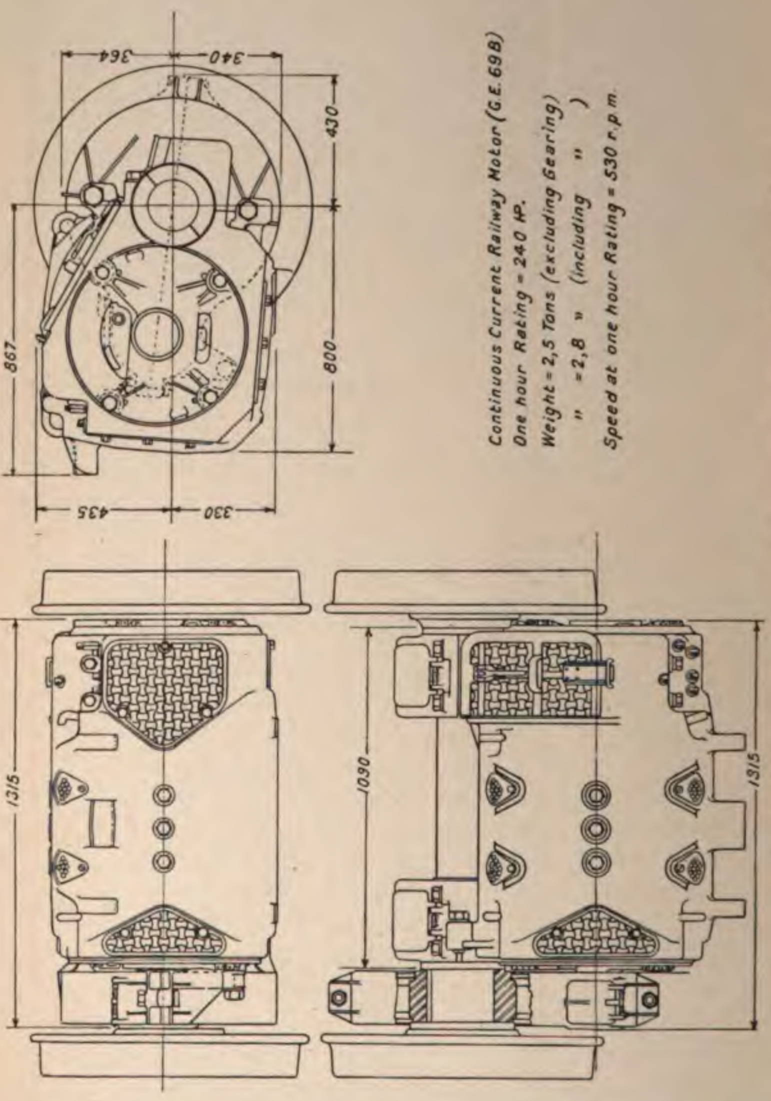

Fig. 164. Outline Sketch of 240 hp Continuous-current Railway Motor. (Scale 1 : 24·4).

figure compares well with our estimated figure of 10 kg per hp for a 250 hp motor weighing 2,5 tons.

In Table XC. will be found many other examples. The table also includes weights of equipments. In column R, the weight of

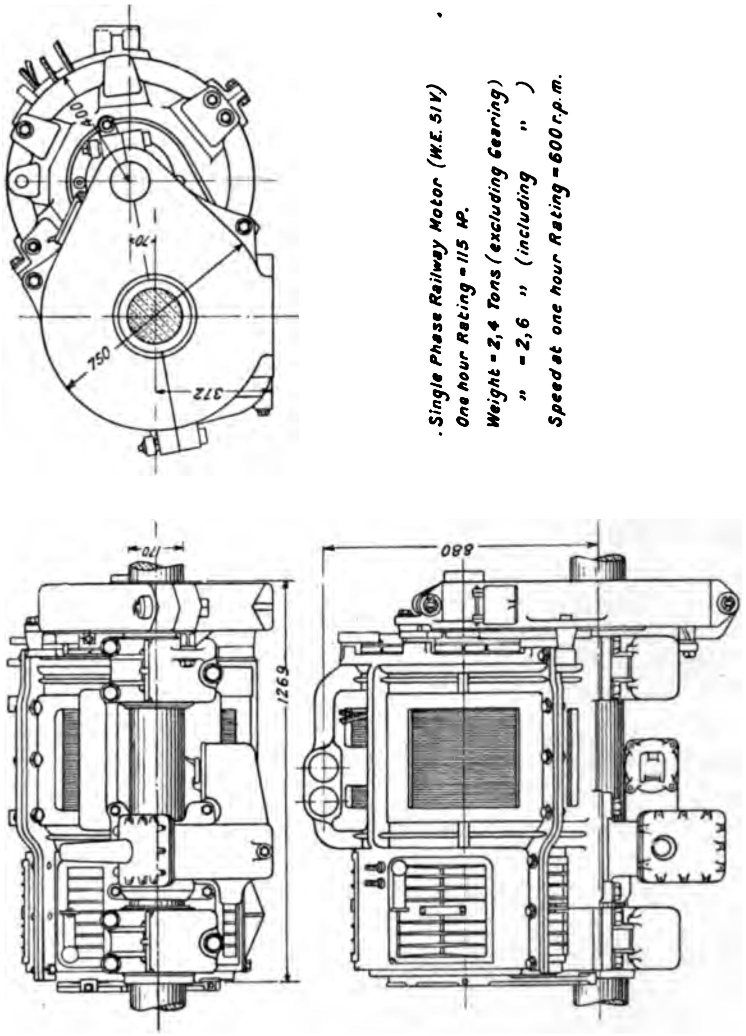

Fig. 165. OUTLINE SKETCH OF 115 HP SINGLE-PHASE RAILWAY MOTOR. (Scale 1 : 24·4).

motor (without gear) per hp per 500 rpm is given. In column S, the figure known as "Valatin's Weight Coefficient"[1] is given. The

[1] See "Electric Railway Engineering," Parshall and Hobart, pp. 372—375.

figures in these columns give a good idea of the relative utilisation of material in the motors.

As regards the power consumption of any railway, the precise efficiency of the motors is not very important *per se*, as the losses in the motor itself are very small in comparison with the losses in transmission and control. Nevertheless, the internal losses determine the heating, and consequently, as has been shown, have a preponderating influence on the rated output and the service capacity of the motor. Thus the lower efficiency of the single phase motor as compared with that of the continuous current motor, though it has but little effect on the overall efficiency of the equipment, is the chief cause of the very much greater weight of the single phase motor for a given rated output. Since the efficiency of the three phase motor is somewhat higher than that of the continuous current motor, the latter is somewhat heavier than the three phase motor for a given rated output.

In further confirmation of the very low weights which are being obtained in three phase railway motors, it is of interest to quote from an abstract of a recent article by Valatin. The abstract was published on p. 277 of *Electrical Engineering* for February 20, 1908, and is to the effect that some of the Ganz Electric Co.'s recent three-phase locomotives are provided with three ranges of speeds, and that the 8-pole motor of a locomotive of this type, built for the Italian State Railways, has a capacity, on the one hour rating, of 1500 hp, and a weight of 13,4 tons (metric), and at a speed of 220 rpm. While building new locomotives of the same type, the manufacturers have recently found it possible, through some changes in the design, to increase the rating of the motors by 20 per cent. to 1800 hp, while the external dimensions and the speed of the motor remain unaltered. Another 8-pole motor of similar construction, designed by the Ganz Electric Co., developing 1100 hp on the one hour rating at 3000 volts, 15 cycles, and 220 rpm., weighs 10 metric tons. Neither of these motors has forced draught. This last motor is suitable for a comparison with the single phase motor of the Pennsylvania locomotive, since neither the weights nor the speeds of the two motors differ materially. The capacity, on the one hour rating, of each motor of the Pennsylvania locomotive is stated to be 500 hp, the tractive force at rated load and normal speed is given at 6,7 metric tons, and the diameter of the drivers is 1830 mm. From these data the speed of the motor is seen to be 236 rpm. The

Continuous Current.	17	Westinghouse .	—	Kelly, *Times Eng. Supplement*, April, 1907	Baltimore, Ohio Metropolitan Ry
	18	G.E. 68 . .	—	Carter. *Journal I.E.E.*, vol. 36, p. 280; *Engineering*, vol. 77, p. 387	Boston Elevated Ry.
	19	G.E. 69C. .	0,197	Sprague, *Electrical Engineering*, Aug. 8, 1907; Sprague, *Street Railway Journal*, Nov. 4, 1905	New York Central.
	20	G.E. 69B. .	0,18	Sprague, *Electrical Engineering*, Aug. 8, 1907; Sprague, *Proceedings A.I.E.E.*, July, 1907, p. 1147	Metropolitan District Ry.; Interborough Rapid Transit; Metropolitan Ry.; Bakerloo; Hampstead; Piccadilly and Brompton, &c.
	21	Dick, Kerr & Co.	—	—	Liverpool Overhead.
	22	Siemens-Schuckert	0,053	*E.B. u. Betr.*, p. 87, 1904	Berlin Hoch u. Unterground.
	23	G.E. 55 . .	—	*Traction and Transmission*, pp. 29—31, 1903	Milan - Gallarette, Chicago W. Side Elect., &c.
	24	Kritzik . .	0,104	*E.B. u. Betr.*, p. 652, Dec. 4, 1906	Vienna Stadtbahn.
	25	Siemens-Schuckert	0,078	*E.B. u. Betr.*, p. 509, Sept. 24, 1906	Cologne-Bonn
	26	Oerlikon T.M. 22 .	0,156	*E.B. u. Betr.*, p. 621, Nov. 14, 1905	
	27	G.E. 84A . . .	0,328	*E.B. u. Betr.*, p. 384, July 14, 1906	New York Central Gearless Loco.
	28	G.E. 76 . . .	—	G.E. Bulletin	Hammersmith & City Ry.; Metropolitan Ry.
	29				
	30				
Three Phase.	31	Ganz Electric Co. .	0,219	*Zeitschrift des Vereins Deutscher Ing.*, Feb. 21, 1903	Valtellina Motor Car.
	32	Siemens and Halske	0,087	—	Marienfeld-Zossen.
	33	Ganz Electric Co. .	0,142	—	Tender for Metropolitan.
	34	Ganz Electric Co., 8	0,505	*E.B. u. Betr.*, No. 6, 1907	Valtellina Ry.
	35	Ganz Electric Co., 8	0,325	*E.B. u. Betr.*, Nos. 1 and 2, 1905	Valtellina Ry. and Simplon.
	36	Ganz Electric Co., 1	0,72	*E.B. u. Betr.*, No. 6, 1907	Valtellina Ry.
	37	Siemens-Schuckert .			
	38	A.E.G. . . .	0,077	—	Marienfeld-Zossen.
	39	Brown Boveri . .	0,061 0,228	*Brown Boveri Bulletin*, May, 1907, No. 145 L	Simplon Tunnel.
	40	Brown Boveri . .	—	*Revue de L'Electricite*, Nos. 2—10	Burgdorf-Thun.

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chief data of the two motors are then as shown in the following Table:—

	Single Phase Motor.	Three-Phase Motor.
Rated capacity in hp	500	1100
Weight, in kg	8800	10 000
Revolutions per minute	236	220
Weight in kg per hp	17,6	9,1

From this Table it appears that the weight, for equal speed, of the single phase motor is double that of the corresponding three phase motor; that is to say, the three-phase motor will develop more than double the power of the single phase motor at the same weight and number of revolutions per minute. Moreover, the single phase motor has forced draft while the three-phase motor depends solely on natural ventilation.

B. *Weight of Extra Equipment.*

There is much difficulty in obtaining reliable figures for the total weight of electrical equipment. Weights of "electrical equipment" are occasionally given in descriptions of railway rolling stock, but it is seldom definitely stated what is included in these weights. The figures given in column *I* of Table XC. represent the weight of equipment per motor, and this weight may fairly be taken as including the motor with gear and gear case, and the weight of the extra equipment *per motor*. The extra equipment should include controllers, switch gear, resistances, transformers, wiring and any auxiliary apparatus, including the current collecting apparatus. When making comparisons, the weight of the pneumatic and other braking equipment should be excluded from the above weight of "electrical equipment." It is impracticable to set up any general rule for calculating the weight of equipment for the various systems, and consequently it is proposed to make comparisons between the figures given in Table XC. These figures for the weights of electrical equipment have been collected from all available sources, and have been corrected and checked at every opportunity. We can only compare them with one another in a general way, however, since, as above stated, it is not always apparent just what is included in the term "electrical equipment."

The first two examples of Table XC. are those given by Sprague in his recent paper before the American Institute of Electrical Engineers.[1] The first is a four motor equipment, each motor (G E A 605) being rated at 75 hp 25 cycles 700 rpm. The total weight of equipment per hp works out at 36,6 kg, and the weight of extra equipment (*i.e.*, excluding the geared motor) at 11 kg per hp. In column M, the weight of extra equipment per motor is expressed as a percentage of the weight of the geared motor. In this case the figure is 44 per cent. The weights given in this and the following case include only those items specified on p. 255. The second example is also a four motor equipment, the motor (in this case a Westinghouse motor) being rated at 75 hp, 15 cycles, 700 rpm. The total weight of equipment per hp works out at 40,6 kg, and the weight of extra equipment at 15,1 kg per hp. This higher weight is probably accounted for by the extra weight of the transformer for 15 cycles, as compared with that for 25 cycles in the first case. The motor itself is somewhat lighter in the second case, and the extra equipment per motor weighs 60 per cent. of the weight of the geared motor. There is, however, little difference between the *total* weight of equipment, whether a frequency of 15 cycles or 25 cycles is employed.

As a further example let us take the two motor equipment of the Heysham-Morecambe line of the Midland Railway. Each of the Siemens motors, of which four have been supplied to this road, has a rated output of 175 hp, and the total weight of equipment appears to be[2] 31,4 kg per hp.[3] The weight of the extra equipment per motor is thus some 83 per cent. of the weight of the geared motor, or 14,3 kg per hp. Very full particulars have been published of the two motor equipment of the Rotterdam-Hague motor coach. As at Heysham, the motors are of the Siemens-Schuckert compensated series type, and are rated at 175 hp each. In this case the total weight of equipment works out at 42,9 kg per hp—much heavier than the corresponding figure given by Dalziel for the Heysham-Morecambe equipment. The weight of the extra equipment per motor is some 150 per cent. of the

[1] A.I.E.E. Proceedings, July, 1907, p. 1188.

[2] See Dalziel's letter in the *Times Engineering Supplement* for April 17 1907.

[3] The *Railway Gazette* for June 19, 1908, has appeared since the above data was compiled and in an article describing the Heysham-Morecambe line, it is stated that the one-hour 75°C. rating specified for these Siemens motors is 180 hp. The weight of the motor, including gearing, is given as 3,12 tons. The total weight of electrical equipment of a motor car with 2,180 hp motors, is 14,4 tons, or 40 kg per hp, a figure 27 per cent. greater than that given by Dalziel in the *Times Engineering Supplement* for April 17, 1907.

weight of the geared motor, or 25,7 kg per hp. The following is a list of the component items of the equipment on the Rotterdam-Hague motor coach :—

Electrical Equipment of One Motor Coach.[1]

	Metric Tons.
One transformer	2,80
High voltage switch	0,20
High voltage resistance	0,20
High voltage fuse	0,01
High voltage cables	0,20
Bow collector	1,00
Two motors with gearing and suspension	6,00
Low voltage cables	0,45
Contactors with case, etc.	1,60
Equipment in driver's compartment	0,30
Master controller	0,20
Motor driven fan	0,25
Motor driven compressor	1,00
Miscellaneous parts	0,75
Total electrical equipment (Or 7,5 tons per motor)	15 tons
The two bogies weigh	10 tons
The car body weighs	22 tons
Consequently the total weight of the motor coach without passengers is	47 tons

Let us compare with the above, some of the figures for continuous current equipments. Take for example the Westinghouse four-motor equipment for the Metropolitan Railway. Each motor is rated at 150 hp, and weighs 2,5 tons with gear. This is not a light motor for its output, but the weight of the *extra* electrical equipment is only 4,52 kg per hp as compared with 11, 15,1, and 14,3 kg per hp for the above mentioned single phase equipments. As another example let us take the two-motor equipment used on the Metropolitan District Railway. Each motor, designated as G.E. 69 B is

[1] This table is reproduced by permission from p. 237 of Vol. II. of *Electrical Traction*, by Messrs. Wilson and Lydall, published by Edward Arnold, London.

(on the one hour 75° C basis) rated at 240 hp,[1] and weighs 2,8 kg per hp with gear. The total equipment weighs 7,3 tons, or 15,2 kg per hp; *under half* the weight per hp for the single phase equipments, which were 36,6, 40,6, and 31,4 kg per hp respectively. The weight of the *extra* electrical equipment, *i.e.*, the electrical equipment excluding the geared motor, is 3,5 kg per hp, or 30 per cent. of the weight of the geared motor.

In Table XCI. are given particulars of a large number of continuous current equipments as manufactured by the General Electric Co. of America and the Westinghouse Co. The data in this table fully confirms the figures which we have adduced above. The G.E. 69 is, in this table, given the nominal rating of 200 hp. As above stated, however, it rates at *240 hp* on the one hour 75° C basis.

TABLE XCI.

Data of Weights of Standard Continuous Current Railway Motors and Equipments. (The figures in the last column are the ratios of the weight of total electrical equipment to the total weight of motors, including gear and gear case.)

Trade Name.	Horse Power.	No. of Motors.	Type of Control.	Weight of Control, kg.	Weight of Motor including Gear and Gear Case, kg.	Total Weight of Equipment, kg. A	Do. per hp, kg.	Weight of Motors, kg. B	Do. per hp, kg.	A ÷ B
G.E. 800	25	2	K 10	427	880	2185	43,5	1760	35,2	1,24
		4	K 12	534	880	4050	40,5	3520	35,2	1,15
G.E. 54	25	2	K 10	427	830	2090	42,0	1660	33,2	1,26
		4	K 12	534	830	3855	38,5	3320	33,2	1,16
G.E. 60	25	2	K 10	427	756	1940	35,5	1510	30,2	1,28
		4	K 12	534	756	3550	34,7	3020	30,2	1,18
Westinghouse 12 A	25	2	K 10	430	1000	2500	50,0	2000	40,0	1,25
		4	K 12	535	1000	4650	46,5	4000	40,0	1,16
Westinghouse 69	30	2	K 10	430	890	2210	37,0	1780	30,0	1,24
		4	K 12	535	890	4150	35,0	3560	30,0	1,17
G.E. 1000	35	2	K 10	427	1000	2430	34,7	2000	28,4	1,21
		4	K 28	615	1000	4615	33,0	4000	28,4	1,16
G.E. 78	35	2	K 10	427	1160	2750	39,3	2320	33,2	1,18
		4	K 28	615	1160	5255	37,5	4640	33,2	1,13
G.E. 58	35	2	K 10	427	980	2390	34,1	1960	28,0	1,22
		4	K 28	615	980	4535	32,4	3920	28,0	1,16

[1] On p. 1326 of the Proc. of the A.I.E.E., Sprague states that 418 G.E. 69 B motors are employed by the Interborough Rapid Transit Co. He states that they "are sometimes 'rated at 200 hp at 300 amp,' but actually test to 241 hp with 75° rise of temperature, according to the standard practice of the American Institute of Electrical Engineers. Several hundred more of these motors are in use on the London Underground Railways, and 268 motors of similar frame, known as the G.E. 69 C, built for 50 volts higher normal operation, nearly 100 less revolutions at the one-hour rating, but developing, notwithstanding, 232 hp with like rise of temperature, are in use on the New York Central Railroad."

Trade Name.	Horse Power.	No. of Motors.	Type of Control.	Weight of Control, kg.	Weight of Motor including Gear and Gear Case, kg.	Total Weight of Equipment kg. A	Do. per hp, kg.	Weight of Motors, kg. B	Do. per hp, kg.	A ÷ B.
Westinghouse 49	35	2	K 10	430	875	2180	31,2	1750	25,0	1,25
		4	K 28	615	875	4200	30,0	3500	25,0	1,20
Westinghouse 92 A	35	2	K 10	430	1030	2540	36,2	2060	29,5	1,23
		4	K 28	615	1030	4850	34,7	4120	29,5	1,18
G.E. 67	40	2	K 10	427	1085	2600	32,5	2170	27,1	1,20
		4	K 28	615	1085	4955	31,0	4340	27,1	1,14
G.E. 70	40	2	K 10	427	1250	2930	36,6	2500	31,3	1,17
		4	K 28	615	1250	5615	35,1	5000	31,3	1,12
G.E. 80	40	2	K 10	427	1270	2970	37,1	2540	31,8	1,17
		4	K 28	615	1270	5700	35,6	5080	31,8	1.12
Westinghouse 38 B	40	2	K 10	430	1020	2700	34.0	2040	25,5	1,32
		4	K 28	615	1020	5500	34,4	4080	25,5	1,34
Westinghouse 68 C	40	2	K 10	430	1040	2600	32,5	2080	26,0	1,25
		4	K 28	615	1040	4850	30,3	4160	26,0	1,17
Westinghouse 101	40	2	K 10	430	1200	2900	36,2	2400	30,0	1,21
		4	K 28	615	1200	5450	34,0	4800	30,0	1,14
Westinghouse 101 C	40	2	K 10	430	1240	3000	37,5	2480	31,0	1,21
		4	K 28	615	1240	5650	35,0	4960	31,0	1,14
G.E. 53	45	2	K 11	460	1250	2960	32,9	2500	27,8	1,18
		4	K 14	1020	1250	6020	33,5	5000	27,8	1,20
G.E. 57	50	2	K 11	460	1350	3160	31,6	2700	27.0	1,18
		4	K 14	1020	1350	6420	32,1	5400	27,0	1,19
		4	Mult Unit	1215	1350	6615	33,0	5400	27,0	1,23
G.E. 90	50	2	K 11	460	1305	3070	30,7	2610	26,1	1,18
		4	K 14	1020	1305	6240	31,2	5220	26.1	1,20
		4	Mult Unit	1215	1305	6435	32,2	5220	26,1	1,23
Westinghouse 39	50	2	K 11	460	1320	3100	31,0	2640	26,4	1,18
		4	K 14	1020	1320	6400	32.0	5280	26,4	1,21
Westinghouse 93 A	50	2	K 11	460	1525	3600	36,0	3050	30,5	1,18
		4	K 14	1020	1525	7200	36,0	6100	30,5	1,18
Westinghouse 56	55	2	K 11	460	1365	3250	29,5	2730	24,8	1,19
		4	K 14	1020	1365	6600	30,0	5460	24,8	1,21
G.E. 87	60	2	Mult Unit	800	1600	4000	33,3	3200	26,7	1,25
		4	Mult Unit	1215	1600	7615	31,7	6400	26,7	1,19
G.E. 74	65	2	Mult Unit	875	1605	4085	31,4	3210	24,7	1,27
		4	Mult Unit	1390	1605	7810	30,0	6420	24,7	1,22
Westinghouse 112	65	2	Unit Switch	510	1550	3600	27,7	3100	24,0	1,16
		4	Unit Switch	1090	1550	7250	27,9	6200	24,0	1,17
G.E. 73	75	2	Mult Unit	875	1830	4535	30,2	3660	24,4	1,24
		4	Mult Unit	1436	1830	8760	29,2	7320	24,4	1,20
Westinghouse 76	75	2	Unit Switch	805	1750	4300	28,7	3500	23,3	1,23
		4	Unit Switch	1650	1750	8600	28,7	7000	23,3	1,23
Westinghouse 85	75	2	Unit Switch	805	2050	4900	32,6	4100	27,4	1,20
		4	Unit Switch	1650	2050	9850	32,8	8200	27,4	1,20
Westinghouse 121	85	2	Unit Switch	805	1950	4700	27,7	3900	23,0	1,20
		4	Unit Switch	1650	1950	8800	26,0	7800	23,0	1,13
G.E. 66	125	2	Mult Unit	1230	1990	5210	20,8	3980	16,0	1,30
		4	Mult Unit	1700	1990	9660	19,3	7960	16,0	1,22
Westinghouse 119	125	2	Unit Switch	805	2090	4980	20,0	4180	16,7	1,19
		4	Unit Switch	1650	2090	10 000	20,0	8360	16,7	1,20
G.E. 55	160	2	Mult Unit	1430	2460	6350	19,8	4920	15,4	1,29
		4	Mult Unit	2450	2460	12 290	19,2	9840	15,4	1,25
G.E. 76	160	2	Mult Unit	1430	2340	6110	19,1	4680	14,6	1,30
		4	Mult Unit	2450	2340	11 810	18,5	9360	14,6	1,25
G.E. 69	200	2	Mult Unit	1535	2830	7185	18,0	5660	14,2	1,27
		4	Mult Unit	2620	2830	13 945	17,5	11 320	14,2	1,23
Westinghouse 113	200	2	Unit Switch	—	3050	8700	21,6	6100	15,2	1,40
		4	Unit Switch	—	3050	—	—	12 200	15,2	—

Evidently we have ample material for concluding that the total weight of a single phase equipment is fully double the weight of the corresponding continuous current equipment of the same rated output. The trucks must consequently be stronger and heavier.

Thus for a schedule speed of some 40 km per hour, with 1,6 stops per kilometer, a train to seat 300 passengers will weigh some 250 tons when equipped for single phase operation, as against about half this weight when equipped for continuous current operation. The energy consumption for this schedule speed will also be fully twice as great. The brake equipment must be more expensive and its maintenance much greater. The wear of rails and permanent way is inevitably greater.

It must be remembered that it is not sufficient to show by electric operation only a very slightly higher acceleration and schedule speed than is attained by steam, but there must be shown a very appreciable gain. The rate of acceleration of a heavy single phase train, quite aside from the limitations imposed by the disabilities of the motors, cannot approach that readily provided by the light train of equal seating capacity equipped with continuous current motors.

Of course there is always the possibility that a light, efficient and satisfactory single phase motor may in the future put in its appearance. Indeed, a main contention put forward by Messrs. Stillwell and Putnam,[1] who are leading advocates of single-phase traction, sets forth that a frequency of 15 cycles per second should be substituted for the 25 cycles, toward which standardisation has been tending. They state that 15 cycle motors would materially surpass 25 cycle motors in the matters of higher efficiency, lower weight, better commutation, and less cost. This may prove to be true. It is at any rate certain that any advantages of lower frequency are in great part offset by the increased weight and cost of the transformers, and by the lower tractive force at starting; and it must appear that this low periodicity does not remove the disabilities of the single phase motor with respect to acceleration and schedule speed. Amongst the possibilities which suggested themselves long ago is that of a good single phase induction motor without a commutator.

It must also be kept in mind that the three-phase system can by no means be ignored as a determinant in the situation; in fact, for long distance, non-stop runs, it has points of superiority over any other system of electric traction as yet put forward. But, at present, it is with the object of obtaining better speed and shorter headway with frequent stops, and the more intense utilization of

[1] "The Substitution of the Electric Motor for the Steam Locomotive" (*Trans. Am. Inst. Elec. Engrs.*, Vol. XXVI, (1907), p. 31).

termini, that resort will be made to electrical methods, and for this work the continuous current system is distinctly superior.

Table XC. contains in addition a few figures relating to three-phase equipments. Thus the two-motor equipment of the Brown-Boveri Simplon Tunnel locomotive has a weight of 25,5 kg per hp, and the extra equipment alone, only 5,9 kg per hp. The motors, in this case rated at 550 hp, were heavier than normal three-phase motors, and weighed as much as 10,8 tons (or 19,5 kg per hp) including gear. This was due to the special arrangements provided for obtaining different speeds.

C. Estimates of the Service Capacity of Single Phase Motors.

The-one hour rating is, of course, only an arbitrary method of stating the capacity of a railway motor, and, as stated on p. 244, it is often more satisfactory (although it entails a large amount of laborious calculations) to take a definite case of a given train and a given schedule, and to estimate, with the aid of the characteristic curves, the performance of the motor under consideration for that particular schedule.

Curves showing the performances of *continuous current* motors on various schedules have been published in nearly all the text books relating to electric traction, and we shall here only work through two or three cases of alternating current single phase motors. For similar examples of the performance of continuous current motors, the reader is referred to "Electric Railway Engineering," by Parshall and Hobart. Let us take the two single phase motors which are foremost in the minds of English traction engineers at the present time, *i.e.*, (1) the 175 hp Siemens-Schuckert motor (in use on the Heysham-Morecambe line), and (2) the 115 hp. W.E. 51 motor (which is to be employed on the London, Brighton and South Coast Railway).

The Energy Consumption of a Train Equipped with Six "Siemens-Schuckert" 175 hp Compensated Series Motors.

In the *Times Engineering Supplement* for April 17th, 1907, Dalziel, the electrical engineer for the Midland Railway, gave the following figures for the component weights of a five-coach train, consisting of three motor coaches and two trailers. Each motor

coach carries two motors. The seating capacity of the train is given as 324 passengers.

Component Weights.

	Tons.
Five coach bodies and underframes	53,0
Seven trailing bogies at 4,5 tons each . . .	31,5
Three motor bogies at 5,5 tons each . . .	16,5
Electrical equipment[1] (including motors) . .	33,0
324 passengers	22,0
Total weight of train	156

This train is to run at a schedule speed of 40 km per hr with a 20 second stop every 1,6 km. (These are not the normal conditions on the Heysham-Morecambe line of the Midland Railway, but are conditions to which Dalziel intends such a train to conform for demonstration purposes.)

Let x = the time in seconds taken to travel the 1,6 km between stops.

Then $\frac{1,6 \times 60 \times 60}{x + 20}$ = schedule speed = 40 km per hour.

Therefore $x = 124$ sec.

The *average* speed $= \frac{1,6 \times 60 \times 60}{124} = 46,5$ km per hr.

The train is equipped with six Siemens-Schuckert compensated series motors, having the characteristics shown in Figs. 166 and 167. The diameter of the driving wheel is taken as 0,83 m, and the gear ratio as 1 : 2,62. The trolley wire voltage is 6600 volts, but the maximum voltage across the motor is only 320 volts. Fig. 166 contains a set of curves drawn up with a view to studying the performance of the motor during the accelerating period. By means of the taps on the transformer, the motor is started at a pressure of 150 volts, the instantaneous starting current being 780 amperes per motor. When the current has fallen to 670 amperes (on account of the speed acquired by the motor), the voltage is increased to 170 volts, and the current immediately rises to 830 amperes. The voltage is increased in steps up to 320 volts,

[1] See Table XC. for details.

the current varying between the limits of 658 and 870 amperes; the average current being 750 amperes. This current per motor corresponds to sufficient tractive force to give the whole train a fairly constant rate of acceleration of about 0,5 m psps, after making a suitable allowance for overcoming tractive resistance. On reaching 320 volts, the motor continues to accelerate " on the motor curve," and the current decreases, until the required maximum speed is reached, when the supply is cut off.

From the curves in Figs. 166 and 167, the input, output and losses of each motor at any point may be estimated. This has been done, and the total input, plotted as a function of the time in seconds, is given in Fig. 168. The whole of that area, the upper portion of which is shaded, represents the total input to the six motors, from the time of starting to the time of shutting off at maximum speed. The top shaded portion represents the internal loss in the motors, and the cross shaded area the gear loss; the remaining area represents the useful input to the axles.

The retardation due to friction on the level is taken as 0,036 m psps, and the retardation at braking at 0,9 m psps. A speed of 64 km ph is reached in 44 sec from starting; and if the supply is cut off at that instant, the train will come to a stop at the end of the 1,6 km run, in 124 sec from starting, thus complying with the arranged schedule. All the above is on the assumption that the particular 1,6 km run considered is perfectly level.

The total area of the input curve of Fig. 168, *i.e.*, the total input to the motors from starting to the instant of cutting off power, amounts to 10 kw hr, or an energy consumption of

$$\frac{10 \times 1000}{156 \times 1,6} = 40 \text{ w hr per ton km.}$$

This is the input to the motors; the input to the train will be somewhat greater, as the efficiency of the transformer has to be included. Assuming the average efficiency of the transformer to be 96 per cent., the energy consumption of the train is 42 w hr per ton km.

The area of the top shaded portion of the input curve in Fig. 168, *i.e.*, the energy lost in the motors, amounts to 1,9 kw hr, *i.e.*, 19 per cent. of the input; consequently the average efficiency of the motor is 81 per cent. The area of the cross shaded portion of the curve, *i.e.*, the energy lost in the gear, is 0,5 kw hr, or 5 per cent. of the input. The area of the remaining portion, *i.e.*, the energy delivered to the axles is $10 - (1,9 + 0,5) = 7,6$ kw hr. The overall efficiency,

excluding the transformer, is thus 76 per cent. and the energy consumption at the axles is therefore:—

$$\frac{7{,}6 \times 1000}{156 \times 1{,}6} = 30{,}4 \text{ w hr per ton km.}$$

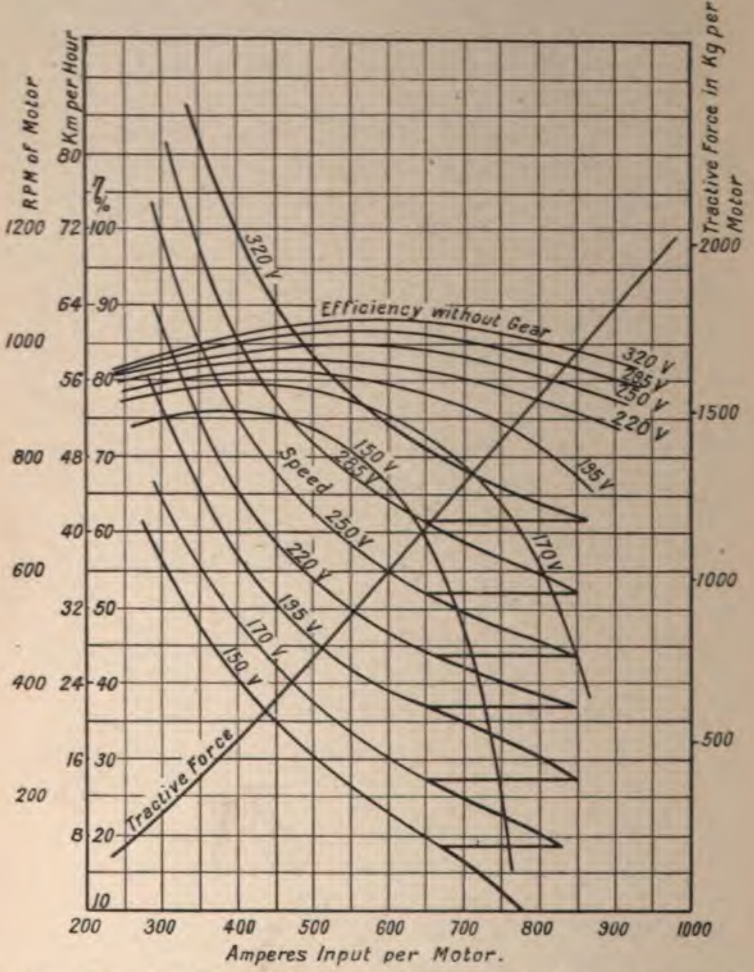


Fig. 166. STARTING CURVES OF SIEMENS-SCHUCKERT 175 HP COMPENSATED SERIES MOTOR.

Including the average transformer efficiency of 96 per cent., the overall efficiency of the electrical equipment is $0{,}76 \times 0{,}96 = 0{,}73$, or 73 per cent. This figure should be compared with the values given in Figs. 146—154, facing p. 239 of Chap. X.

The following figures are of interest :—

Average kw per motor during acceleration	= 136 kw
Maximum kw per motor during acceleration	= 238 kw
One hour rated kw per motor (175 hp)	= 148 kw

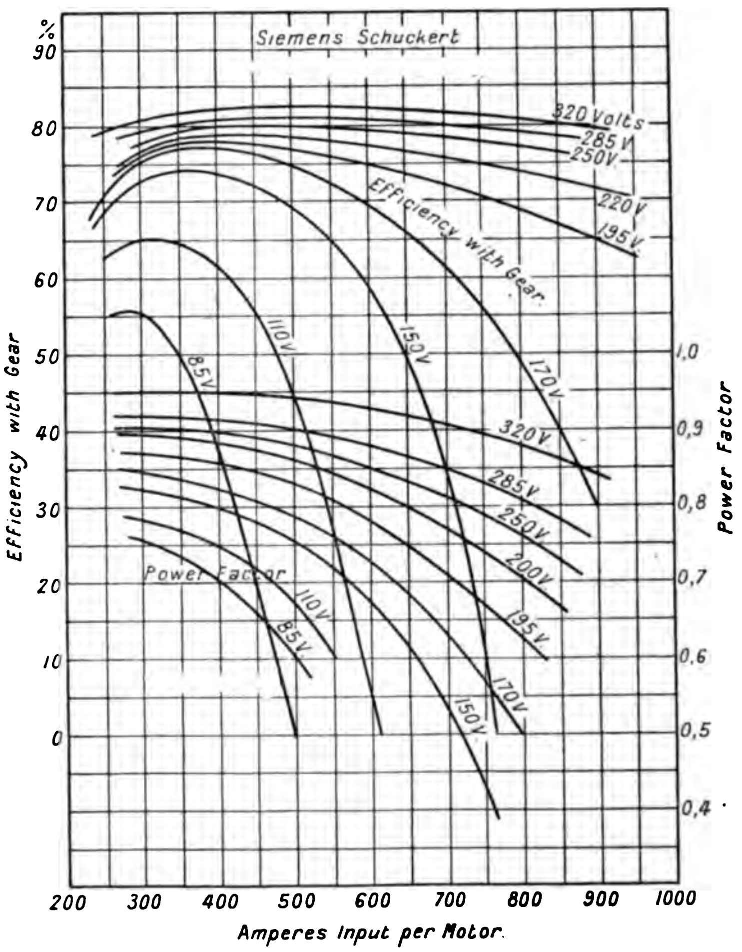


Fig. 167. Efficiency and Power Factor Curves of Siemens-Schuckert 175 hp Compensated Single Phase Motor.

Time elapsing from start to start = 124 + 20 = 144 sec.

$$\text{Average kw per motor} = \frac{10 \times 3600}{6 \times 144} = 41{,}7 \text{ kw.}$$

Ratio of rated load to average load $\frac{148}{41,7} = 3,5$.

Thus we find that the average load during acceleration is within

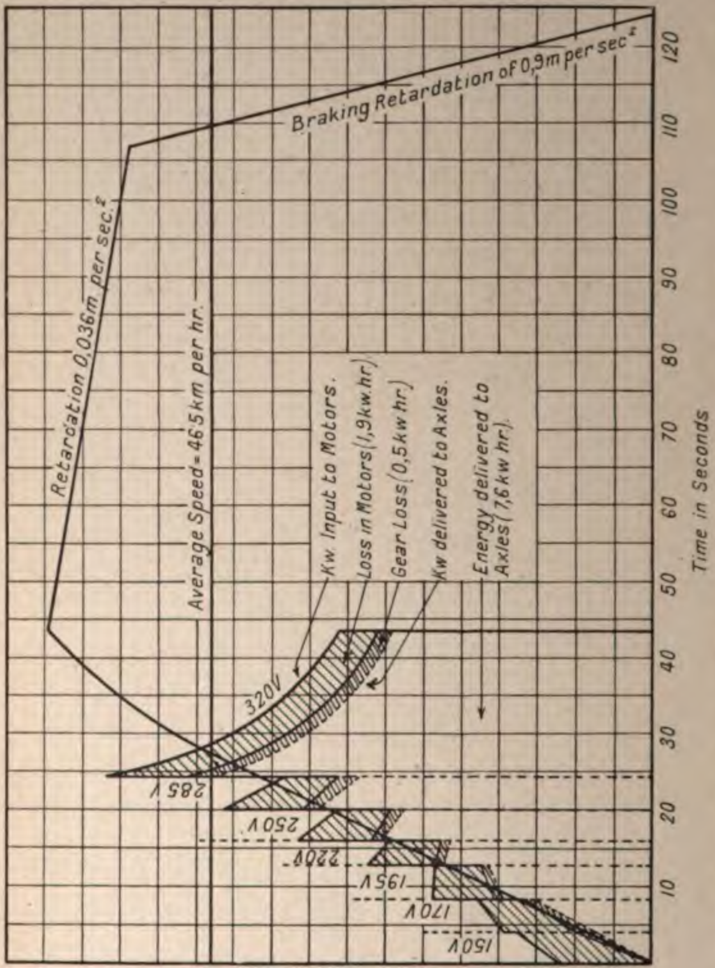


Fig. 168. Speed Time Diagram and Energy Input Curves for a 156-Ton Five Coach Train provided with 6.175 HP Motors.

Schedule Speed 40 km per hour over a 1·6 km run with 20 sec. stops.

the one-hour rated load. To obtain some idea of the heating of the motors, let us see how many watts per ton are wasted internally. We have seen that the energy lost in the motors during acceleration

is 1,9 kw hr. The time from start to start is 144 sec; therefore the average watts per motor are

$$\frac{1{,}9 \times 3600 \times 1000}{144 \times 6} = 7930 \text{ watts.}$$

The weight of one motor without gear is 2,77 tons. Therefore average watts per ton =

$$\frac{7930}{2{,}77} = 2860 \text{ w per ton.}$$

This is a high figure, and can only be attained by forced ventilation. The losses are shown separately in Fig. 169.

After subtracting the losses from the total output, we found that 7,6 kw hr were delivered to the axles of the train for the single run. We can check this figure from a consideration of the kinetic energy of the train at the instant the power is cut off, as this 7,6 kw hr must have been utilized to set the train in motion. A small amount of this energy, however, must have been utilized in overcoming the tractive resistance.

The kinetic energy of the train consists of two items, firstly, that due to the translational motion of the train; secondly, that due to the rotational motion of wheels and armatures. The first item is easily calculated. Thus, kinetic energy = $\frac{1}{2}$ M V^2, and expressed in kilogram meters =

$$\tfrac{1}{2} \times \frac{\text{weight in kg}}{9{,}81} \times (\text{velocity in meters per sec.})^2$$

Thus at the instant of cutting off the supply, when the train has attained to a speed of 63,5 km per hr:—

$$\text{The kinetic energy} = \tfrac{1}{2} \times \frac{156 \times 1000}{9{,}81} \times \left(\frac{63{,}5 \times 1000}{3600}\right)^2$$
$$= 2\,480\,000 \text{ kg m}$$

But one watt hour = 367 kg m. Therefore the kinetic energy due to the translational motion is equal to $\frac{2\,480\,000}{367 \times 1000} = 6{,}76$ kw hr.

The second item, the kinetic energy of the rotating parts, can here be taken as being some 8 per cent. of the first item. Therefore, total kinetic energy = 6,76 × 1,08 = 7,3 kw hr. Energy must also be supplied to the train during the accelerating period in order to overcome the tractive resistance; this amount is not easily calculated, as the speed is not constant. It would probably be about 0,3 kw hr, which would make the total energy input to the axles

7,6 kw hr, as was obtained by deduction from the motor characteristics.

Alternative Run.—It will be noticed that the average starting current is some 750 amp, or about 65 per cent. in excess of the

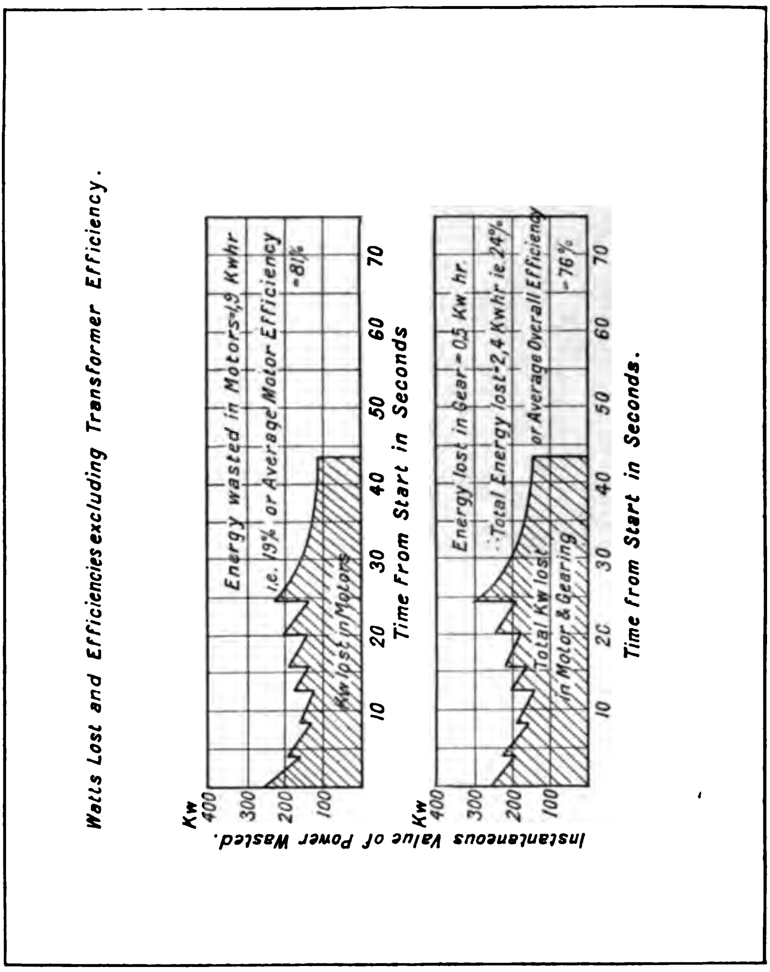


Fig. 169. Curves showing the Losses in the Motors during the Run. Separated from Total Input Curves of Fig. 168.

current corresponding to the normal rated load. At starting, the induced current in the short circuited coils is, in single phase motors, so great a source of difficulty as regards commutation, that it is preferable to start with a low voltage, and consequently a low current.

Fig. 170 gives an alternative method of starting; the starting voltage being only 85 volts per motor. The corresponding speed-time diagram and energy input curve are given in Fig. 171. By

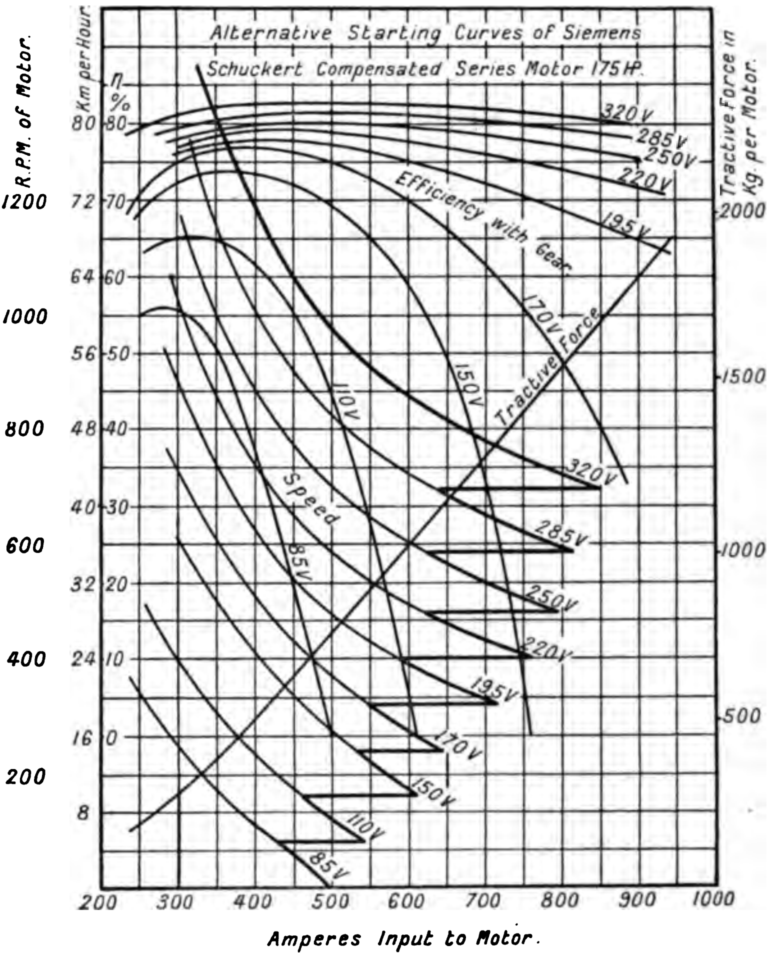


Fig. 170. Speed Characteristic and Tractive Force Curves of Siemens-Schuckert Single Phase Motor.

means of an additional tap on the transformer, the motors may be started with a pressure of only 85 volts per motor. As can be seen from the speed-ampere curve for this pressure (in Fig. 170), the instantaneous starting current is then 500 amp. When the current

has fallen to about 430 amp (on account of the speed acquired by the motor), the pressure is increased to 110 volts, and upwards

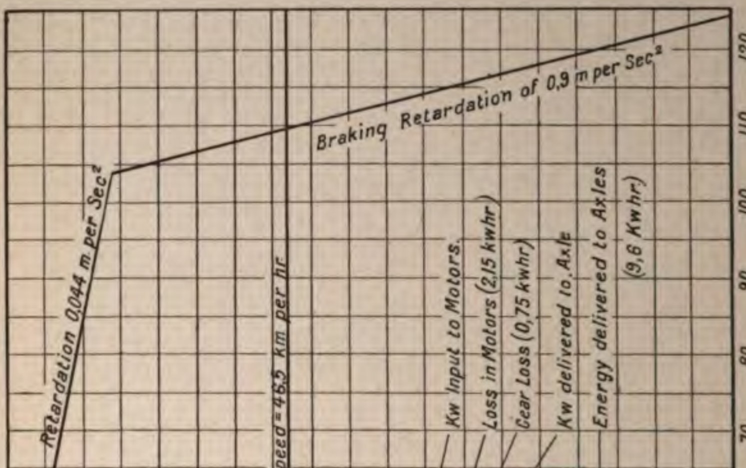


Fig. 171. Alternative Speed Time Diagram and Energy Input Curves for a 156-Ton Five Coach Train provided with 6·175 hp Motors.

Schedule Speed 40 km per hour over a 1·16 km run with 20 sec. stops.

in steps to 320 volts. The motors are running at a comparatively high speed on these last steps, and the current can be increased without incurring commutation difficulties. Thus in the particular case considered in Fig. 170, the maximum current is 850 amp. The

mean rate of acceleration in this case is of course much less than that obtained by the first method, and consequently the power will have to be supplied to the train for a longer time, in order to reach the necessary maximum speed. The speed-time curve and the energy input curves, under the above conditions, are given in Fig. 171. The average rate of acceleration (until the "motor curve" is reached) is 0,34 m psps, the maximum speed 71 km ph; and as the speed is higher, the retardation during coasting has been taken at 0,044 m psps. The braking retardation has been taken at 0,9 m psps, as in the previous case. The energy input to the motors, the internal loss in the motors, and the gear loss, are represented by the areas of the respective input curves as was explained for the first case. For this example the following figures only need be given :—

Total energy consumed by the six motors is 12,5 kw hr, or 25 per cent. in excess of the consumption in the first case. The input to the motors is therefore

$$\frac{12,5 \times 1000}{156 \times 1,6} = 50 \text{ w hr per ton km.}$$

Assuming, as before, an average transformer efficiency of 96 per cent., the energy consumption of the train is 52 w hr per ton km. The internal losses in the motors amount to 2,15 kw hr ; the average efficiency of the motors is therefore 82,8 per cent. The gear loss amounts to 0,75 kw ; the average overall efficiency is therefore 77 per cent., excluding the transformer. The energy delivered to the axles is 9,6 kw hr, or 38,5 w hr per ton km.

Including the average transformer efficiency of 96 per cent., the overall efficiency of the equipment is $0,77 \times 0,96 = 0,74$, or 74 per cent., only 1 per cent. higher than the efficiency in the first case.

The following figures are of interest, and should be compared with those on p. 265 :—

Average kw per motor during acceleration = 116 kw
Maximum kw per motor during acceleration = 232 kw
One hour rated kw per motor (175 hp) = 148 kw

Average kw per motor from start to start = 52 kw.

$$\text{Ratio of rated load to average load} = \frac{148}{52} = 2,85.$$

During acceleration 2,15 kw hr are wasted in the motors. The time from start to start is 144 sec ; therefore the average watts per motor are

$$\frac{2,15 \times 3600 \times 1000}{144 \times 6} = 8960 \text{ watts.}$$

The weight of one motor without gear is 2,77 tons. Therefore average watts per ton $= \frac{8960}{2,77} = 3240$ watts per ton.

The average watts per ton, during acceleration only, are of course

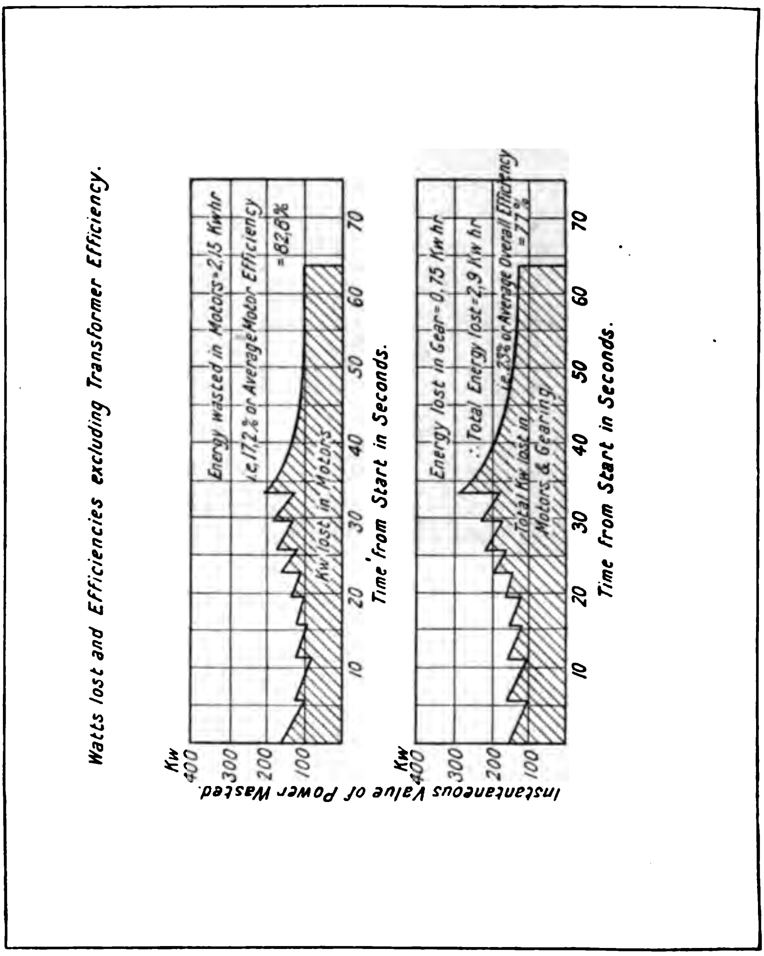


Fig. 172. CURVES SHOWING THE LOSSES IN THE MOTORS AT ANY INSTANT DURING THE RUN. SEPARATED FROM TOTAL INPUT CURVES OF FIG. 171.

higher; in the particular case considered, they amount to

$$\frac{2,15 \times 3600 \times 1000}{64 \times 6 \times 2,77} = 7280 \text{ watts per ton.}$$

The losses are shown separately in Fig. 172.

In the first case considered, in which the rate of acceleration until reaching the "motor curve" portion of the accelerating period

was 0,50 m psps, we found that the total energy supplied to the axles of the train was 7,6 kw hr. Furthermore, on p. 267 we found that nearly all this energy was utilized in giving the train the velocity of

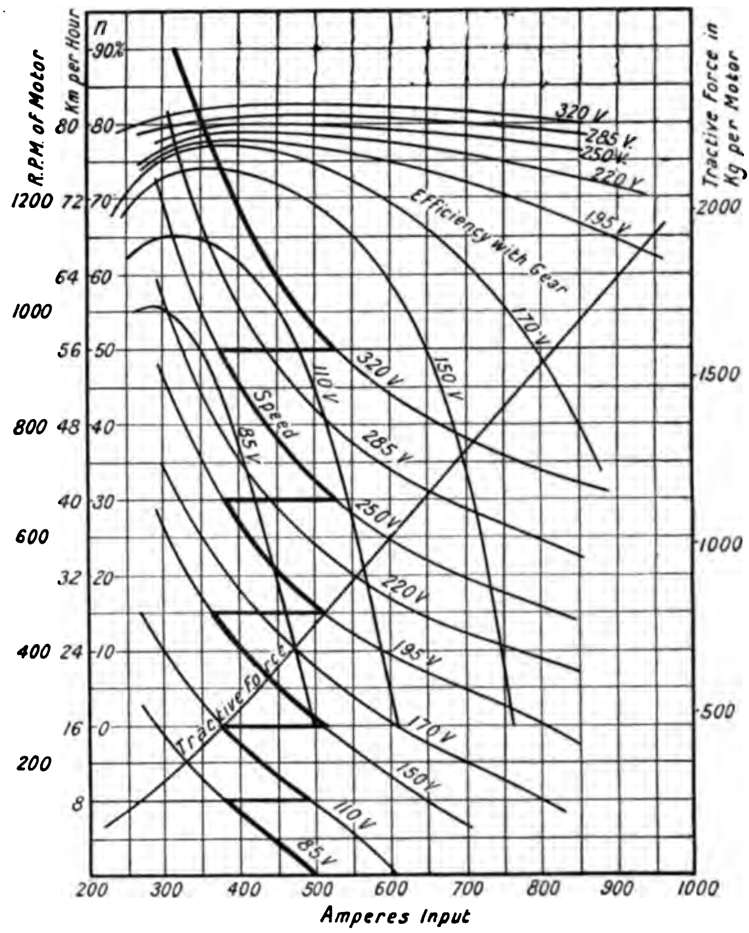


Fig. 173. Speed Characteristic and Tractive Force Curves of 175 HP Compensated Siemens-Schuckert Single Phase Motor.

63,5 km per hr. In the second case we found that 9,6 kw hr had to be delivered to the axles, *i.e.*, 26 per cent. more than in the first case. This shows the importance of a high rate of acceleration, as in both cases the schedule and average speeds were the same; the rates of acceleration were 0,50 and 0,34 m psps respectively.

At the instant of cutting off the supply in the second case, the speed of the train is 71 km per hr. From this figure and the weight of the train, we can deduce the total energy input as in the previous case.

$$\text{The kinetic energy} = \tfrac{1}{2} \times \frac{156 \times 1000}{9{,}81} \times \left(\frac{71 \times 1000}{3600}\right)^2$$
$$= 3\ 100\ 000 \text{ kg m}$$

But 1 watt hour = 367 kg m. Therefore the kinetic energy of the train due to the translational motion is 8,45 kw hr.

The second item, the kinetic energy of the rotating parts, can be taken, as before, as being some 8 per cent. of the first item. Therefore the total kinetic energy = 8,45 × 1,08 = 9,15 kw hr. The energy which must be supplied during the accelerating period (which is longer in this second case) to overcome the tractive resistance will bring this amount up to 9,6 kw hr: which last figure was the estimated value of the energy input to the axles from a consideration of the motor characteristic curves.

Second Alternative Run.—Fig. 173 shows yet another cycle of starting operations. In this case the average starting current is 440 amp. Were this alternative chosen, the train would not reach a sufficiently high speed to be able to complete the run in 124 sec. This is shown clearly in Fig. 174 which is the speed-time diagram for the case considered. Braking is commenced at such an instant, that the train will stop 124 sec after starting. The average speed is only 35,5 km per hr, and so the distance covered will be only 1,22 km, instead of 1,6 km. The train cannot attain to a schedule speed of 40 km per hr under these conditions. This last case was given in order to emphasise the fact that the motors must be able to withstand, during some stage of the accelerating period, a starting current considerably in excess of the normal current at rated load.

Limitations of Single Phase Motors.—The single phase motor is very limited as regards the capacity for overload, and in order to clearly demonstrate this, the characteristic curves for the 175 hp compensated series motor discussed above are given in the following figures (Figs. 175—178) in a somewhat different form to that in which they were given in Fig. 166. In this case the speed, current, power factor and efficiency are plotted against the output in horse power as abscissæ. From this series of curves it will be seen that the maximum output is sharply defined at each operating voltage, and, further, that the maximum output decreases rapidly with decreasing voltage. Thus in the case of this motor,

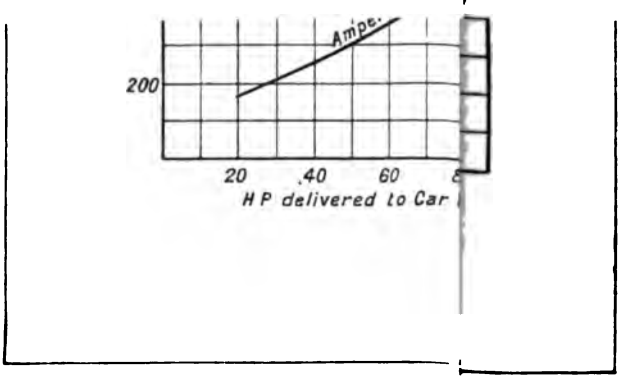


Fig. 177. Performance Curves of S kert 175 hp Compensated Series Single Phase Pressure of 220 Volts

To face p. 275.

rated at 175 hp, the maximum horse power at the normal voltage of 320 volts is about 230 hp, or only 26 per cent. more than the one-hour rated output. At 275 volts the maximum output is

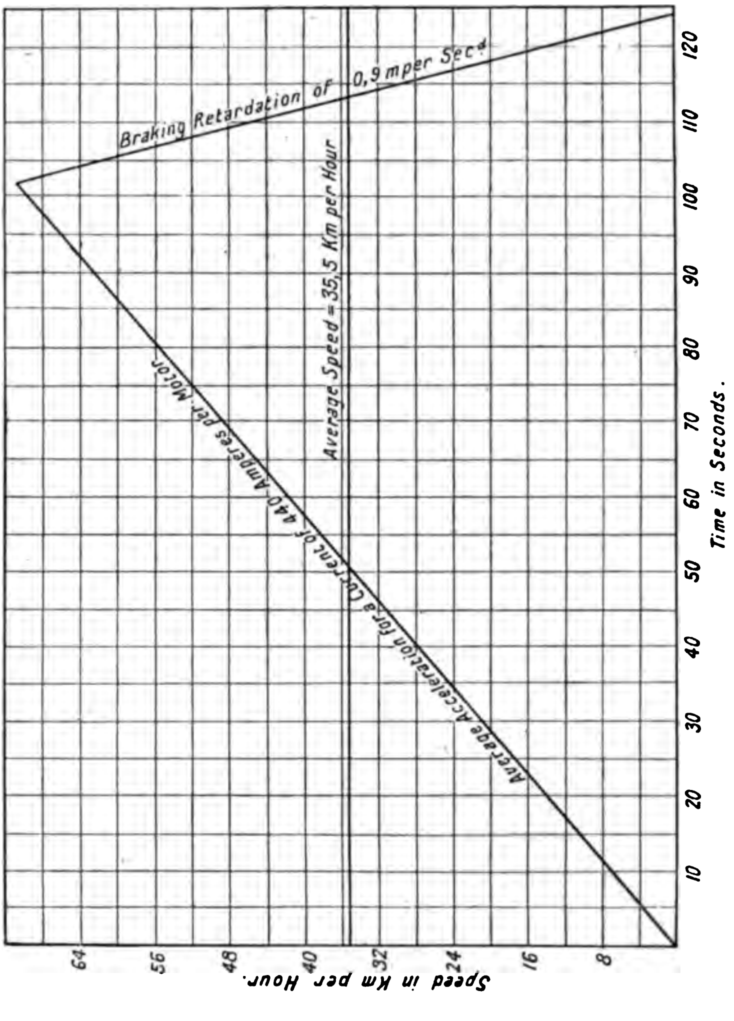


Fig. 174. Alternative Speed Time Diagram for a 156-Ton Train (Five Coach) showing the Impossibility of Attaining the Required Schedule Speed with Limited Acceleration.

about 160 hp, and at 220 volts only 95 hp, while at 150 volts it is only some 36 hp. Of course, these low voltages are only used starting, but the torque, required to obtain the necessary high rate of acceleration, is also low. All single phase motors are limited in this way, but the continuous current motor has a

momentary capacity some three or four times its rated output, and is thus in this respect much superior to the single phase motor. Although these curves are for the compensated series commutator motor, it must be remembered that the compensated repulsion commutator motor is limited in the same respect.[1]

Let us now examine the case of a single phase motor of the compensated repulsion type.

The Energy Consumption of a Train Equipped with Eight "A. E. G. Winter-Eichberg" 115 hp Compensated Repulsion Motors.

The *Electrician*, for June 14th, 1907, contains an article by Dawson, the consulting engineer for the L.B. & S.C. electrification undertaking. Figures are given for the energy consumption of a train consisting of two motor coaches each equipped with four motors (*i.e.*, eight motors in all), and one trailer coach. There are two classes, and seating accommodation for 188 persons. The total weight of the train is given as 132 tons. The particular journey taken as an example is the run between Battersea Park and Peckham Rye, a distance of 6,3 km. There are four stops in this run (exclusive of start and stop at Battersea and Peckham Rye respectively).

The run is made under the following conditions :—

Schedule speed, 42 km ph ;
Average speed, 48,5 km ph ;
Duration of stop, 15 sec ;
Rate of braking, 1,0 m psps.

In order to simplify the calculations it is assumed that the entire run is over a level track. Fig. 179 shows the characteristic curves for the W.E. 51 115 hp single phase compensated repulsion motor, eight of which are to be used on the train under consideration. In order to attain to the required scheduled speed, it will be necessary to work the motors on the cycle shown in Fig. 179, *i.e.*, with a starting current of 26 amp (the current in the motor is, of course, much greater ; the amperes here mentioned are those measured on the primary of the transformer).

The gear ratio is taken as 3,3 and the diameter of the driving wheel as 1,06 m, which values are those of the actual gears and wheels of the L.B. & S.C. cars. The above cycle of operations

[1] See also an article by the author in *The Light Railway and Tramway Journal*, June 10th, 1904, pp. 447–451.

will give the necessary draw-bar pull and speed at all points of the cycle, to correspond with the speed-time curve given in Fig. 180.

A single run, representative of the complete 6,3 km run, is that between Denmark Hill and Peckham Rye. The speed-time and

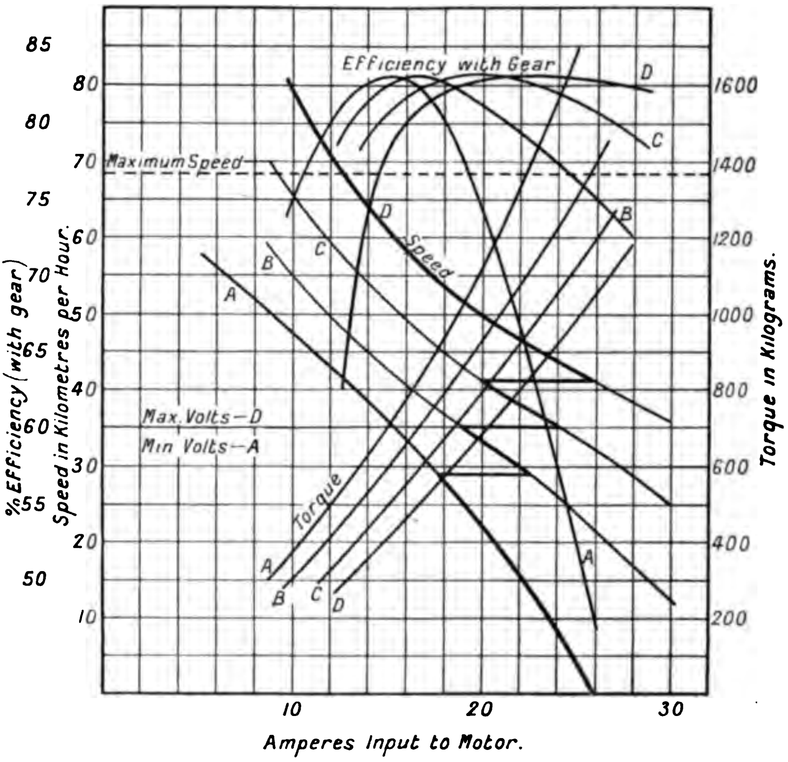


Fig. 179. SPEED, AMPERE. AND TORQUE CURVES OF W.E. 51, 115 HP SINGLE PHASE COMPENSATED REPULSION MOTOR.

input curves of the run are shown in Fig. 180. From these curves the following data can be obtained :—

(1) Maximum speed necessary in order to cover the 1,21 km distance between stops is 68,5 km ph ;

(2) The average speed over this distance is 49 km ph ; and

(3) The schedule speed with a 15 sec stop is about 42 km ph.

These are practically the same as the corresponding figures for the whole run of 6,3 km, consequently the particular run under consideration is quite representative.

The input curve of Fig. 180 represents the power input from the eight motors to the axles of the train at any instant, and consequently from this curve we can obtain by integration the total energy (in this case about 8,2 kw hr) utilized by the train in

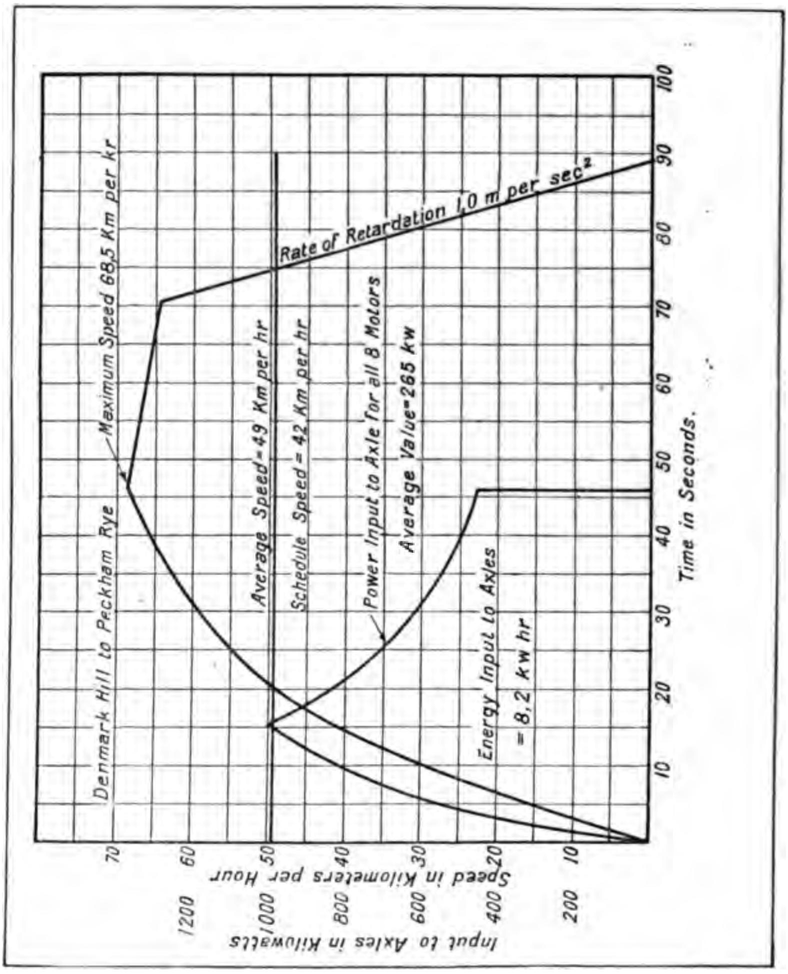


Fig. 180. Curves of Speed and Time and of Energy Input to Axles for 132-Ton Train. Length of Run = 1,21 km. Duration of Stop = 15 sec.

running up to the maximum speed of 68,5 km ph, or in other words, the total energy of the train due to its momentum at the instant of maximum speed, together with that amount of energy which has been spent in overcoming tractive resistance, which last,

as we have seen, is only small compared with the energy due to momentum.

The average efficiency of the motors (including gear) obtained from the efficiency curves given in Fig. 179 (above the torque characteristic curves) is about 75 per cent. The average value of the input of energy to the axles, as obtained from the curve of input in Fig. 180, is some 265 kw, or 33,1 kw per motor. If the average efficiency is 75 per cent., then the average input to each motor will be

$$\frac{33,1}{0,75} = 44,2 \text{ kw.}$$

Therefore the average losses in gear and motor during the accelerating period are $44,2 - 33,1 = 11,1$ kw.

The gear loss is very much the same at all loads, and can be taken as about 4 per cent. of the input to the motor at rated (1 hour 75° C) load. The 115 hp motor will have an input at rated load (assuming an efficiency of 82 per cent.) of some 105 kw, 4 per cent. of which is 4,2 kw. The average loss in the motor itself is therefore $11,1 - 4,2 = 6,9$ kw.

The motor weighs 2,4 metric tons without gear, consequently the average value of the watts per ton during acceleration will be

$$\frac{6900}{2,4} = 2880 \text{ watts.}$$

The average value of the watts per ton from start to start will be about half the above, which is low compared with the figure found for the Heysham 175 hp motors (see pp. 267 and 272). But the train in the present instance weighs 132 tons and carries eight motors, each weighing 2,4 tons (excluding gearing), or an aggregate motor weight of 19 tons, which works out at 6,9 tons of train per ton of motors. The hypothetical train studied in connection with the 175 hp compensated series motors had a weight of 156 tons, and the six 175 hp motors each weighed (exclusive of gearing) 2,77 tons, or an aggregate motor weight of only 16,6 tons, which works out at 9,4 tons of train per ton of motors. Since the schedules studied were not widely different, the difference in watts lost per ton may thus be partly accounted for.

The efficiency of the motor at rated load is about 82 per cent. with gear, or about 86 per cent. without gear. If the input is 105 kw, the energy lost in the motor itself *at rated load* is some 14,7 kw, or about 6120 watts per ton of material.

Returning to the train problem, we have seen that the energy input to the axles is about 265 kw on the average, or for the total

run of 6,4 km, which takes 9 minutes, about 40 kw hr, or $\frac{40 \times 1000}{6,3 \times 132} = 48$ w hr per ton km. The input to the train, assuming an average efficiency of the motors (with gear) of 75 per cent., and an average transformer efficiency of 97 per cent., will be some 66,5 w hr per ton km.

These examples of the calculation of the energy consumption of a train serve to show under what conditions the motors have to work, and the fact that they are actual cases of particular single phase motors which are to work under definite conditions as to acceleration, maximum speed, etc., on known lines in England, lends especial interest to the investigations. Trains are already running at Heysham, and it is stated that by 1909, trains will be in commercial operation on the electrified portion of the L.B. & S.C. Railway.

D. Single Phase versus Continuous Current Systems of Railway Electrification.

The advocates of the single phase system of railway electrification generally draw attention to such weaknesses of the continuous current system as the rotary converter, but they omit to point out the disadvantages that must be suffered in order to avoid this undesirable adjunct. Each system must be considered as a whole, and it is not an advantage to transfer a weakness from *terra firma* to what is always the weakest portion of the system—the train equipment.

There is too much made of the alleged lower total capital cost due to the absence of rotating sub-station plant and to the use of high-pressure distributing as well as high-pressure service conductors. Where there is a saving in one place it is far more than offset in another. Thus the electrification undertaking of the L.B. & S.C. Railway is costing at least 50 per cent. more than would have been the case if the continuous current system had been adopted. At the time that the contract was entered into, some of the most reputable technical papers stated, with every appearance of authority, that the outlay on the scheme would be approximately a quarter of a million sterling.

The route can easily be inspected, and sufficient has been published, at one time and another, of the trains, the service, and the electrical equipment, to enable a fairly close estimate of the cost of electrification by the continuous current system to be made. There

are to be eight trains of three coaches each, two of these being motor coaches, each equipped with four of the Allgemeine Elektricitäts Gesellschaft's 115 hp single phase motors and accessories. The trains are to make the journey between London Bridge and Victoria, a distance of 8,6 miles, in 25 minutes, stopping at the ten intermediate stations. The contract does not include a generating station, as the power is to be bought.

The following is a very prodigal estimate of the outlay that such a system would require if electrified by the continuous current system. The 8,6 miles of double track route will, including sidings, run into some 20 miles of track work which must be equipped for electrical operation without interfering with the traffic on the railway. The cost of straight third rail with bonding of track rails does not exceed £1000 per mile, or £20 000 in all. Let us add another £20 000 to this for special work (although this is much beyond what could be required), and also £20 000 for cables (again an excessive amount), making the cost of the complete track work £60 000. The coaches, including trucks, will cost £1800 to £2000 each, and for the 24 coaches we will allow £50 000. The electrical equipment of the three-coach train to do the service required (say, four 180 hp motors and accessories) will cost less than £2000, so that we shall be liberal if we allow for the equipment of the eight trains a sum of £20 000. Two sub-stations will be sufficient, each containing rotary converters or motor generators with an aggregate rated capacity of 2000 kw per sub-station, but with capacity for intermittent overloads of over twice this amount. This cost is easily covered by £5 per rated kw, or £20 000 in all.

The cost of the electrification by the continuous current system is therefore as follows:—

	£
Trackwork	60 000
Coach bodies and trucks . . .	50 000
Train equipments	20 000
Sub-stations	20 000
Unforeseen contingencies . . .	10 000
	£160 000

Considering the competition at the present time, it is highly probable that this figure would be much reduced if the matter were put up to public tender.

So much then for a comparison of the actual cost of the L.B. & S.C. Railway electrification with a very liberal estimate for doing the same work by the continuous current system, an estimate, moreover, that can easily be checked, as all the apparatus is standard. Furthermore the *operating* costs on this railway will also much exceed the figures that could be attained with continuous current operation. The saving in sub-station expenses is trifling compared with the extra cost of power due to the heavier train, the much larger cost of train equipment due to the employment of double the number of motors (and these each more costly to maintain) and the greater maintenance cost of a 6000 volt overhead conductor as compared with a third rail.

The success of the single phase system for railways as distinguished from tramways is still in the region of pious hopes. All that has been carried out at present is under the supervision of the manufacturers. The characteristics of the continuous current system are well known. If the North-Eastern or the Lancashire and Yorkshire Railway, when they come to consider further electrification, adopt the single phase system, it will be much more to the credit of this system than its adoption by railway companies who have not been allowed to consider any other system.

If only it is clearly understood in railway circles that electrical engineers have developed far better means of railway electrification, the author is personally well satisfied that the L.B. & S.C. Railway should have adopted the single phase system. They will thus, although at considerable expense, provide the railway and engineering world with a practical demonstration of its inferiority for such a service. If, on the other hand, railway directors should conclude that this **single phase monstrosity** is the best thing that engineers have to put forward for railway electrification, the impending exposure will, when it arrives, discredit electrical engineering, and will be all the more disastrous the longer it is deferred.

On p. 447 of the *Light Railway Journal* for June 10th, 1904, the present author opened an article with the following paragraph: "From the standpoint of its technical merits, the single phase motor is at present a factor in the railway electrification problem only in so far as a promising possibility of its further improvement at an early date entitles it to consideration." Four years have elapsed since the publication of that statement, and no substantial progress is in evidence; on the contrary, side by side with the disabilities to which attention was then drawn have arrayed themselves

further grave disabilities which were at that time not foreseen. These must all now be ruthlessly exposed in order that railway electrification on sound lines shall not be unduly retarded.

In Messrs. Stillwell and Putnam's American Institute paper on the "Substitution of the Electric Motor for the Steam Locomotive," to which allusion has already been made on p. 260, the standpoint is taken that the single phase system is the only system worthy of consideration for railway electrification. "Where, ten years from to-day," they ask, "will be the 1200 or the 1500 volt continuous current systems which have been suggested as substitutes for high potential alternating current systems in heavy electric traction?" These gentlemen appear to have allowed a desire, shared by all engineers, to secure the best system for long distance work, to supplant sufficient study of adverse details in the single phase system. The author's opinion is that within ten years, continuous current systems as applied to railway electrification will employ line pressures more of the nature of 2000 or 3000 volts, and these systems will, in all probability, have come into extended use. The single phase delusion will meanwhile have been exposed (at the expense of the capitalists) and the system discredited.

Railway electrification on an extensive scale will, however, have been retarded for years — first, in consequence of the waiting policy which is being maintained pending the completion of the single phase experiments; secondly, in consequence of the prejudice against electric operation of railways which will inevitably follow as a consequence of the analysis of the results obtained with single phase plant.

It is highly desirable that railway people should realise that a large number of electrical engineers dissociate themselves, though rarely openly, from the claims put forward by the single phase school. This is important for the reason that there is a wide range of railway work where electric operation is of demonstrable advantage if undertaken on sound lines. For long-distance non-stop runs, however, it will for some time be difficult or impossible for trains depending for their power on electric energy supplied over long distances to compete with trains hauled, as at present, by steam locomotives. It is only for such cases, however, that single phase systems can possibly hold their own in comparison with high tension continuous current systems. It is very unfortunate that electrical engineers should be handicapped in their endeavour to enter the legitimate field offered by urban, suburban and interurban sections of railways (where the

traffic is intense and consists in operating trains at short headway, and with frequent stops, at relatively high schedule speeds), for the sake of the vague possibility of some time entering, with this single phase incubus, on a field of railway work where the steam locomotive is, by right of merit, most strongly established.

For such "legitimate" work, high acceleration is all-important. This is readily obtained by the continuous current motor; it is impossible with heavy trains with the single phase motor, a mere apology for a motor at the best, which is seen at its very worst when starting and during acceleration. Another important feature for a service with frequent stops is low weight of train, as almost all the energy delivered from the motor is devoted to imparting momentum to the train during acceleration, and is immediately thereafter converted into heat at the brake shoes (although a considerable proportion of it could well be restored to the line by one or other of the now well developed systems of regenerative control).

Overhead versus Third Rail.

The overhead constructions developed in connection with the single phase system, as worked out for light interurban roads, are excellent. They are proving, however, less generally adaptable to main line railways. A number of experienced steam railway engineers have pointed out various difficulties entailed by the overhead construction, which are avoided by the use of the third rail, and electrical engineers cannot do better than take advantage of their obviously sound suggestions in this matter. Indeed, in many ways the progress of railway electrification would be accelerated were more heed given by electrical engineers to the comments made by steam railway engineers with reference to electrification proposals.

The gratifying rarity of third rail accidents, and the comparative freedom from troubles of any kind, justify the assertion that, with suitable provisions for the protection of the third rail, pressures very considerably in excess of the now customary 600 volts, can be used with entire satisfaction. The cost of overhead construction as supplied to main line railways has been far in excess of the estimates, and constitutes one of the heaviest burdens of the ill-omened single phase system. Nevertheless, for situations where steam railway engineers would prefer the overhead construction, it represents a sound, though expensive, proposition, and it will doubtless have a place in railway electrification, although this will probably

be subsidiary to the third rail. There is no objection to providing a train with both overhead and third rail collecting devices, so that it may proceed over sections equipped in either of these two ways.

It is desirable at this juncture to allocate the natural fields for overhead and third rail constructions respectively. In the recent discussions of continuous current and single phase systems the latter have shown up to such poor advantage that there is no need to raise the voltage of the continuous current system in establishing a comparison. But in the *serious* question of electricity *versus* steam for operating main line railways, the former has in the latter a very formidable competitor whose status is sound, and the use of higher continuous current voltages is a legitimate feature to incorporate in proposals for main line railway electrification.

There are a number of sound alternative methods of employing high tension continuous current. The author would like to mention one of them but does not wish to thereby sacrifice his freedom to advocate others where more suitable. The author would suggest that an 800 volt system is satisfactory for sections over which the traffic is heavy and frequent. On outlying sections where the frequency is less, either a pressure of 1600 volts from third rail to track, or of 800 volts on each side of the track as neutral, provides a good basis. For sections with a still less frequent traffic, 3200 volts could be employed. For these sections the overhead construction will be less objectionable, and will be comparatively inexpensive, owing to the continuous and uninterrupted character of the route. Various simple and obvious means are available for advantageously employing a given train equipment over these different sections. There is, of course, nothing final in the pressures mentioned; 600, 1200 and 2400 volts might be preferable owing to the large number of 600 volt equipments already in service.

A recent instance of the high cost of overhead construction is that cited on p. 915 of the *Street Railway Journal* for May 25, 1907, by Mr. Wilgus, Vice-President of the New York Central Railroad. Mr. Wilgus' statement is as follows: "Much has been said also about the cost of overhead single phase construction. In 1906 one authority has estimated it at £3200 per mile, but the actual cost has been £10 000." This would partly account for the need of so large a sum as £250 000 for the L.B. & S.C.'s 8 mile experiment. This sum, it will be remembered, does not include the necessary generating plant. As already pointed out, not over

two-thirds of this sum would have been required had the continuous current system been employed, nor would anything like five years have been required for carrying through the work.

The high-voltage continuous current system is now of proven practicability, and affords the most satisfactory system of heavy electric traction. With the single phase system, it has not been sufficient to adopt *reasonably* high trolley voltages, but it has been necessary to adopt otherwise *objectionably* high trolley voltages owing to the serious question of drop on the rail return; for, with a given current, the drop on a given length of rail return is many times greater with single phase than with continuous current, and hence the current must be kept down to a much lower value than other considerations render advisable. In other words, a needlessly high trolley voltage becomes indispensable with the single phase system, out of consideration of the importance of avoiding too considerable a drop of voltage in the rail return. The available methods for offsetting the drop on the rail return are too expensive and complicated to be generally employed.

In the case of the continuous current system, a pressure of 3000 volts is quite sufficient for heavy electric traction, and leads to very satisfactory trolley constructions. Setting aside the question of the rail return difficulty, some 3000 volts could well be employed with the single phase system were it not for the consideration that greater weights of rolling stock and equipment and consequently greater amounts of energy are required for the single phase system and that the lower power factor and lower efficiency of the single phase system lead to a much greater current being required, for a given amount of energy at a given voltage, than is the case with a continuous current system for the same voltage. Thus 4000 or 5000 volts would be a more suitable pressure for the single phase system were it not for the limitations imposed by the drop on the rail return, which renders it necessary, for main line traction, to employ from 10 000 to 20 000 volts when the single phase system is used. The single phase advocates are making a virtue of necessity when they point with satisfaction to these high voltages.

The technical press has, during the last few years, contained so great a number of papers and articles devoted to extolling the advantages of the single phase system of railway electrification that, in order that the impression that this system is carrying all before it shall not become too deeply-rooted, it is important, before dismissing the subject, to call attention to certain carefully

considered statements which have been put forth by a number of engineers who are in substantial agreement with the author as to the inferiority of the single phase system.

In the course of the discussion on a recent paper by Jenkin,[1] Carter made an instructive comparison between the continuous current and single phase systems, which has the advantage of being derived from actual experience instead of from pious aspirations. In order to refute Jenkin's conclusion that the single phase system was the best for general use on English railways, Carter pointed out the necessity of proving it true for railways in urban and suburban districts, since it was only in the case of such railways that electrification in any shape or form had, to the present, been proved an economical policy. In making the comparison he was careful to argue only from matter that was public property rather than express his own private opinion. The comparison was between the equipments that it had been decided to adopt on the L.B. & S.C. Railway, one of whose lines in South London was being equipped for single phase operation, and those used on the Metropolitan District Railway. It was on this occasion shown by Carter that even the following, at first glance, extreme statements erred entirely in favour of the single phase system.

1. The amount of driving machinery required per seat was more than twice as great in the single phase as in the continuous current system.

2. The first cost of this machinery per seat was considerably more than twice as great in the single phase system.

3. The maintenance of this machinery per seat was considerably more than twice as great in the single phase system.

4. The energy consumption per seat was greater in the single phase than in the continuous current system.

It was then pointed out that in the case of urban railways worked by the continuous current system, the outlay on train equipment was from one-fourth to one-third of the total cost of electrification, and that no possible saving on sub-stations could atone for the greater cost of train equipments in the single phase system. Moreover, the third rail is cheaper than overhead construction, whilst the generating plant is certainly no cheaper in the single phase system than in the continuous current system. It was therefore unnecessary to labour the point further, as it was demonstrated that for this class of

[1] Read on November 13th, 1906, before the Institution of Civil Engineers (see Proc., vol. cxlvii., pp. 28—101).

service—the *only* class in which electrical engineers had hitherto been able to justify their pretensions—the single phase system was entirely inferior to the continuous current system, both in first cost and in cost of working.

In an article in the May, 1907, issue of *Cassier's Magazine*, Behrend dismisses the single phase question as follows: "The single phase railway mania has even now hardly run its course, although a thoughtful consideration of the case should have long since enabled engineers to see that it is a 'forced idea.'" Behrend points out that "the very much reduced output of both generators and motors, if operated single phase, the reduced efficiency, the impaired regulation, the increased heating and less stability of single phase motors and generators, connected with the increased cost resulting from the greater amount of material required; these form the main reasons which induce me to call the recent attempts which have been made in the utilization of single phase currents a forced idea. . . . If single phase currents are to be used successfully, a new *creative idea* must be introduced which will do away with some of the disadvantages peculiar to the present single phase apparatus."

E. Capital Outlay and Operating Expenses of Electric Traction.

Mr. F. W. Carter has very kindly consented to the inclusion in this treatise of a report which he has made concerning the capital outlay and operating expenses of electric traction on railways with heavy trains making few stops. The author of the present treatise is of opinion that this report of Mr. Carter's sums up the situation in an incomparably clear way, and that there is no escape from the conclusions arrived at. Mr. Carter's report in full is as follows:—

Up to the present time, practically all experience in the use of electricity as the motive power for railways has been confined to thickly populated urban districts, where certain advantages of operation, tending to improve the service and thus increase the traffic, have rendered electrification desirable even if sometimes more costly than steam operation. In the few cases where electrical operation has been adopted for other than urban passenger service, as, for instance, in the case of the long distance trains running in and out of the New York terminus of the New York Central and Hudson River Railroad, the considerations that have led to electrical working have been other than those of mere economy. Such

schemes, therefore, however interesting and important, have no bearing on the question of the general use of electrical energy for operating railways.

In order that electrical operation may be considered economical, as compared with steam operation, it is necessary, either that the operating expenses should be less by an amount more than sufficient to pay interest on the additional capital outlay involved, or that the increased operating expenses should be justified by improved facilities. In the case of urban and suburban passenger service, in which stops are frequent, the fact that, with electrical operation, a large reserve of power is available for producing a high rate of acceleration, enables a higher schedule speed to be attained without increasing the maximum speed and the energy consumption. The service is thus improved, and it is in this improvement that the economy of electrical operation is usually found. In the case of interurban service, however, where stops are, in general, a considerable distance apart, there is little to be gained by a high rate of acceleration. On the less important branch lines, there is some advantage in being able to operate small units with fair efficiency, as is evidenced by the growing use of self-propelled motor coaches on such lines. It is one of the advantages of electrical operation, assuming that a multiple-unit system of train control is employed, that each coach or group of coaches shall carry the motors necessary to drive it, so that the motive power of the train is proportional to the number of coaches. Thus the motors can always be used efficiently, and the speed is practically unaffected by the length of the train. Nevertheless, where the traffic is sufficient to warrant it, as on the great main lines joining the larger towns, heavy trains of many vehicles are to be preferred. Such trains, as compared with smaller ones in larger numbers, require less power per vehicle, especially at high speeds, cost less for drivers' wages, whilst involving fewer signalling operations and using the track to greater advantage.

The main line heavy traffic being much the most remunerative and important class handled by the majority of our railways, it is necessary, if electrical operation is to become general, that economy should be shown in the operation of this class of traffic. As indicated above, it does not appear that any considerable improvement in facilities would result from electrical operation, whilst the fact that all trains in a district would be dependent on a central source of power and on a more or less complicated

distributing system, must be accounted a disadvantage of no small magnitude. Accordingly the justification for electrical operation must in this case be sought principally in the actual saving of operating expenses.

It is proposed here to discuss in a general manner the electrical operation of heavy passenger trains making few stops and running at fairly high scheduled speeds, with special reference to the capital outlay involved and to the cost of operation. The problem is an important one, not only in determining whether general electrification would prove an economical policy, but because, if such should be found to be the case, the system of electrification adopted would doubtless be chosen to suit the class of service under consideration here.

Several sets of figures will be obtained for capital outlay and operating expenses, representing different methods of operation, and limiting values of the quantities involved. Both continuous current and single phase systems will be discussed, and in the case of the former, both average and minimum values will be obtained for the expenses. In deducing the minimum values, the highest efficiencies, the lowest costs, and the most advantageous operating conditions that have been found in practice, or can reasonably be expected, will be assumed. It is not likely, however, that the most favourable conditions will be possible in every element of a system, and, in particular, that the highest efficiency will be associated with the lowest capital costs and the minimum amount of stand-by plant. Thus the lower limit is not likely to be attained in practice, and in the opinion of the writer (Mr. Carter), the figures given as *average* results will form a better guide to a realizable solution.

The figures obtained for the total operating expense are to be compared with the item scheduled as "locomotive power" in the railway companies' returns, increased by the interest on the capital represented by locomotives. It is not suggested that these figures would be scheduled as locomotive power in the case of an electrified railway. Rates, and other standing charges, would be included elsewhere, the maintenance of line conductors would doubtless be included in maintenance of way, whilst interest on capital would not be charged to expenditure, but is legitimately included in this comparison.

It is proposed to base the discussion on a particular passenger train, of weight and dimensions fairly typical of the main line expresses seen on many of our railways. The train may be

considered as made up of ten bogie coaches, similar to those which formed the subject of Mr. J. A. R. Aspinall's tests on Train Resistance.[1] The weight of the train, with its normal passenger load, but excluding electrical equipment, will be taken as 250 tons, and its length as 520 feet (160 meters).[2] The electrical equipment, of which the weight and cost alone concern us, will be considered as comprising not only the driving motors, controlling apparatus, cables, switches and air compressor or vacuum exhauster motors, but also all panels, brackets, ducts, and other arrangements for supporting the electrical apparatus, and constructional material used in installing the same, all drivers' brake valves, air compressors, vacuum exhausters, main reservoirs, etc., together with all that is additional to trucks and underframes. In fact, comparing a ten-coach train as described by Mr. Aspinall with a ten-coach electrical train of the same capacity, all essential difference in cost and weight will be charged to electrical equipment.

The train resistance will be deduced from Mr. Aspinall's formula[1] for trains having oil axle boxes, namely:—

$$R = 2{,}5 + \frac{V^{\frac{5}{3}}}{50{,}8 + 0{,}0278\,L} \text{ lb per ton}$$

where V is the speed in miles per hour and L is the length of the train in feet

$$\left[\text{or } R = 1{,}12 + \frac{V^{\frac{5}{3}}}{250 + 0{,}45\,L} \text{ kg per ton,}\right.$$

where V is the speed in kilometers per hour, and L is the length of the train in meters.]

For the train under consideration, for which $L = 520$ ft. [160 meters], the formula reduces to

$$R = 2{,}5 + \frac{V^{\frac{5}{3}}}{65{,}3} \text{ lb per ton.}$$

$$\left[\text{or } R = 1{,}12 + \frac{V^{\frac{5}{3}}}{320} \text{ kg per ton.}\right]$$

Inasmuch, however, as Mr. Aspinall's results were obtained by means of a dynamometer in the drawbar behind a locomotive, the formula does not include the head resistance, which is experienced

[1] Proc. Institute of Civil Engineers, vol. cxlvii., p. 155.

[2] In Mr. Carter's original report, the data are given in feet, miles, and pounds. The author has ventured to add the metric equivalents.

by the locomotive itself, or in the case of an electric train, by the leading coach. In order to take some account of this, the variable term in the above formula has been increased by 5 per cent., leading to the working formula:—

$$R = 2,5 + \frac{V^{\frac{5}{3}}}{62,1} \text{ lb per ton} \qquad (1.)$$

$$\left[\text{or } R = 1,12 + \frac{V^{\frac{5}{3}}}{332} \text{ kg per ton}\right]$$

Inasmuch, again, as the electrical equipment, whilst doubtless adding somewhat to the air resistance, will not increase it in anything like the proportion of the added weight, the above formula has been applied to the unequipped train of 250 tons only, whilst the extra resistance due to the electrical equipment has been taken at the uniform rate of 4 lb [or—say—2 kg] per ton. Thus, if E be the equipment weight, the total train resistance at speed V is:—

$$250\ R + 4\ E \text{ lb} \qquad (2.)$$

$$[\text{or } 250\ R + 2\ E \text{ kg}].$$

The mean speed of the train whilst actually running is assumed to be 0,75 of the free running speed on a level track. The scheduled speed, including service stops, is assumed to be 0,70 of the free running speed. The mean train resistance will be greater than that at the mean running speed, inasmuch as the portion depending on the speed varies as a power higher than the first. For instance, if a run be made for 1 mile [1,61 km] at a speed of 80 miles per hr [129 km per hr] and 1 mile at 48 miles per hr [77 km per hr], the mean speed will be $0,75 \times 80 = 60$ miles per hr [97 km per hr], whilst the mean train resistance will correspond to 65,3 miles per hr [105 km per hr]. Consequently, in obtaining the work done against train resistance, the mean value has been taken as that at 0,8 of free running speed. The energy output of the motors, expended in work against train resistance, will be 2 w hr per train mile per pound of mean train resistance [2,73 w hr per train km per kg of train resistance].

In order to take account of the kinetic energy lost in braking at station and signal stops, slacks, etc., it is assumed, as sufficiently characteristic of this service, that the speed of the train is reduced from free running speed to a half of this, once in every 15 miles [24 km]. Assuming that the effect of rotary inertia is equivalent to an addition of 10 per cent. to the weight of the train, the effect of these slacks is to require an output from the motors of

0,00155 MV^2 w hr per train mile—M being the total weight of the train in tons and V the free running speed in m ph, [or 0,000374 MV^2 w hr per train km where V is the free running speed in km ph].

Energy will also be used in shunting and in idle journeys. Additional energy will be required where the train resistance is increased by curves, crossings, bridges, tunnels, winds, etc. The general effect of grades is usually also to increase the energy consumption slightly. In order to take account of these factors the bare figures given by the above formulæ have been increased by 15 per cent., making finally the mean output of the motors when in service:—

2,3 × mean train resistance + 0,00179 MV^2 w hr per train mile

[or 3,1 × mean train resistance + 0,00043 MV^2 w hr per train km, when the train resistance is expressed in kg per ton and V in km per hr].

This quantity divided by the average efficiency of the equipment gives the energy input. The writer has found from experience that the above dynamical method of obtaining the energy consumption, if used with care, yields excellent results.

In electrical apparatus where it is necessary to develop so much power in so confined a space as obtains in the case of train-driving motors, the heating of the vital parts of the motor will always be a limiting feature, since all available kinds of insulating material are more or less damaged or weakened by high temperature. It is necessary, therefore, to make the amount of energy to be dissipated the basis from which to derive the particulars of the train equipment. Thus, although no experience is available on the electrical operation of the class of traffic now under consideration, the investigation is made upon a basis derived entirely from experience in railway operation, and independent of the special features of the class of traffic.

Railway motors of large size, such as require bogies of, say, 8 ft. [2,4 m] wheel base, if completely enclosed and without artificial cooling arrangements, are capable of dissipating, under service conditions from 1000 to 1250 w per ton of motor with an ultimate temperature rise of approximately 70° C, as indicated by a thermometer placed in contact with the hottest accessible part. The above figures for the power that can be dissipated include iron and copper loss in the motor, with the commutator losses due to brush contact resistance

and friction. In order to allow for exceptionally great train resistance or weight, breakdown in train equipment, etc., it is advisable to base the calculations on the smaller of the above figures, viz., 1000 watts per ton of motor, where there are no artificial cooling arrangements, since 70° C rise by thermometer is as much as should be allowed in service. Where the motors are cooled by forced draught, however, possibly twice as great a dissipation might be attained with suitable arrangements.[1] This assumes that the motors are on the trucks of the coaches, where they cannot well be given much attention. In a locomotive a somewhat greater draught might be used for cooling, as the motors can be kept under observation and deleterious matter more carefully strained from the air before forcing it into the motors. In the following it will be assumed that the motors are mounted on the trucks of the coaches, which is, in the matter of operation, preferable to the use of locomotives, and is in any case sufficient for the purpose of the present general discussion.

The following tables give the constants assumed in the calculations. In these tables, column A gives average values found in practice employing the continuous current system with motors cooled by natural draught. Column B gives to each item the best values that can be expected with this system. Column C gives the best values that can be expected using the continuous current system with motors cooled by forced draught. Column D gives the best values to be expected using the single phase system with motors cooled by forced draught. In the continuous current system, the supply to the motors is not necessarily at the low pressures usual on urban systems, but to the degree of approximation possible here, the exact pressure of supply is not important. However, rather large figures have been allowed for cost and maintenance of line conductors, to provide for a considerable quantity of protecting boards. In the single phase system the constants have usually been chosen more favourable than could be attained at present, in order to make allowance for future improvements.

Remarks on Table XCII.—The difference between the first two items represents energy used in controlling the motors, in operating the air compressors, etc., and in the case of column D the loss in the main transformer. The difference between the second and third items represents energy lost in gears, which has throughout

[1] The examples worked through in connection with the Siemens Schuckert 175 hp compensated series motor on pp. 261 to 274 indicate this to be the case.

been taken as $4\frac{1}{2}$ per cent. of the input. Motor-bearing friction, being a very small quantity, may be taken as included in this. If the motors were assumed gearless, however, the final results would not be greatly affected. The fourth item includes iron and copper losses in the motor, with commutator losses both of brush contact resistance and friction. In the class of service considered, the train operates for much of the time at free running speed where the brush friction will be large. The single phase motor will have an

TABLE XCII

Characteristics and Conditions of Carter's Four Alternative Projects.

	A	B	C	D
Average efficiency of complete equipment	84	85	85	78
Average efficiency of motor, including gear	87,5	88,0	88,0	82,5
Average efficiency of motor, excluding gear	92,0	92,5	92,5	87,0
Average loss in motors (per cent. of input)	8,0	7,5	7,5	13
Ratio of motor weight to equipment weight	0,6	0,6	0,5	0,5
Watts dissipated per ton of motor	1000	1000	2000	2000
Watts dissipated per ton of equipment	600	600	1000	1000
Average efficiency of transmission (bus bars to train)	78	80	80	89
Power used in generating station in per cent. of power generated	6	4	4	4
Standby plant at peak of load in per cent. of total	30	20	20	20
Trains in service at peak of load in per cent. of total	62,5	62,5	62 5	62,5
Load factor (per cent. for 365 days per annum)	35	45	45	45
Train miles per annum per mile of single track	10 400	10 400	10 400	10 400
Train km per annum per km of single track	10 400	10 400	10 400	10 400

especially large brush friction on account of the large number of brushes which are required, whilst it will, in virtue of its characteristics, require to be run for much of the time at reduced voltage and correspondingly reduced efficiency.

With equipment weight defined as above, the motor weight is usually about 60 per cent. of this in the continuous current system with natural draught. If with forced draught, it is possible to reduce the motor weight by a half, other apparatus being unchanged;

this weight would become 43 per cent. of the equipment weight To assume it at 50 per cent. is probably somewhat favourable to forced draught. This figure is also fair to the single phase system in which the controlling gear includes heavy transformers.

The efficiency of transmission, in the case of the continuous current system, is taken from experience, but it is estimated for the single phase system. The number of trains in service at the peak of load, and the load factor, have been estimated from main line time-tables, and are both probably a little high. The load factor may be defined as the ratio of the average load for the year to the average during the time of the maximum daily peaks. It is assumed that the full load capacity of the plant, exclusive of standby, is just sufficient to provide for the average load during the time of the maximum peaks—its overload capacity taking care of variations above the average.

The last item gives the number of trains passing over each mile (kilometer) of track, being the average for the whole kingdom. It is obtained from the Board of Trade returns for 1905 by dividing the total train mileage (400 millions) [or a total train kilometerage of 645 million] by the total length of running track of 38 430 miles (62 000 km). It is used in estimating the expenses per train mile (train-kilometer) for upkeep, etc., of line conductors.

TABLE XCIII.

Capital Outlay with Carter's Four Alternative Projects.

	A	B	C	D
Cost generating station, £ per kw capacity	18	15	15	15,75
Cost sub-stations, £ per kw generating station capacity	10	7,5	7,5	2,5
Cost transmission lines, £ per generating station capacity	3	2,5	2,5	2
Cost train equipment, £ per ton weight	120	90	110	120
Allowance for contingencies	5	5	5	5
Cost line conductors, £ per mile of single track	1200	1000	1000	1300
Cost line conductors, £ per km of single track	750	620	620	810

Remarks on Table XCIII.—The cost of the generating station includes site, buildings, docks, sidings, etc., as well as the actual plant. The minimum for the single phase system is taken at 15*s*.

per kw more than for the continuous current system, inasmuch as single phase generators are about one-third more expensive than three-phase generators of equal full load and overload capacity. The cost of sub-stations also includes sites, buildings, and all necessary for completeness. The cost of transmission lines depends on the lay-out of the distribution system, as well as on the capacity, but being a comparatively small item, an average figure per kw has been assumed. The figure has been taken 10*s*. per kw lower in the single phase system than in the continuous current system, although there would be more copper for a given pressure between conductors, since the lines would doubtless be carried on the gantries provided for supporting the overhead line conductor, so that a line of poles would be saved.

The cost of train equipments is rather more when forced draught is employed than when the motors are naturally cooled, inasmuch as the total cost will not be diminished in the same proportion as the weight, whilst the arrangements for providing the forced draught will add to the cost. The single phase equipments will be more expensive than continuous current equipments, principally on account of the motors being more complicated in construction.

The cost of line conductors in the case of the continuous current system includes a third rail, bonding of track rails, protecting devices to prevent accidental contact with the third rail, the equipment necessary for an average amount of special work, sectionalising and isolating switches, and other accessories. In the single phase system the cost includes the overhead conductor mounted on insulators and carried in general by gantries spanning the line, bonding of track rails, boosting transformers, special work at bridges, tunnels, turnouts, etc., with sectionalising switch cabins and other accessories. A cheaper form of construction might be adopted on a tramway or unimportant branch line, but the figure given is certainly as low as would be possible if the substantial construction characterising British railways were adopted.

Remarks on Table XCIV.—The cost of power includes coal, water, oil, waste, etc., wages, office expenses, removal of ashes, and all expenses in connection with the repair and renewal of plant. Even in the largest and most modern generating stations, carrying a railway load, it is rare for this cost to be less than 0,275 pence per kw hr (*i.e.*, per "unit") of output, and the minimum figure of 0,225 pence is hardly likely to be reached unless coal can be obtained at

pit-bank prices and other circumstances are favourable. The sub-station expenses are derived from experience in the case of the continuous current system, and are estimated for the single phase system. The standing charges include rates, taxes, insurance and the like, on generating station and sub-stations. They are estimated at 3 per cent. of the first cost in the case of column A, and at 2½ per cent. in the case of the other three columns, and are expressed in the table in pence per kw hr generating station output. The

TABLE XCIV.

Operating Expenses with Carter's Four Alternative Projects.

	A	B	C	D
Generating expenses, pence per kw hr output	0,275	0,225	0,225	0,225
Sub-station expenses, per kw hr output from generating station	0,025	0,02	0.02	0,006
Standing charges, generating station and sub-station	0,094	0,0428	0,0428	0,0348
Maintenance transmission lines per kw hr output from generating station	0,006	0,0045	0,0045	0,0045
Maintenance train equipments per mile per hp	0,00125	0,0011	0,00125	0,002
Maintenance train equipments per km per hp	0,00078	0,00069	0,00078	0,00124
Maintenance line conductors per train mile	0,55	0,46	0,46	0,75
Maintenance line conductors per train km	0,342	0,286	0,286	0,465
Drivers' wages per train mile	2,99	2,99	2,99	2,99
Drivers' wages per train km	1,86	1,86	1,86	1,86
Interest on capital, excluding line conductors (in per cent.)	3,75	3,75	3,75	3,75
Interest on capital, line conductors, per train mile	1,04	0,86	0,86	1,12
Interest on capital, line conductors, per train km	0,65	0,54	0,54	0,70

maintenance of transmission lines is a small matter, and the figures given are taken from urban practice.

The maintenance of train equipments depends on the number of equipments per train, or on the horse power. The figures given are expressed in terms of the horse power required at free running speed on level track, and are approximately correct when the motors are large and mounted on the bogies of the coaches. The single phase system as compared with the continuous current system will have approximately twice as many motors for a given

horse power, and the motors, being more complicated, will be more costly to maintain, so that the figures given are really much more favourable to the single phase system than to the continuous current system, and allow a great deal for future improvements in the former system.

The maintenance of line conductors in the continuous current system is not a heavy item, as the third rail does not appear to wear appreciably with use. Including inspection, renewal of protection boards, occasional replacement of broken insulators and bonds, with the bonding of renewed track rails and the extra material and labour involved when sleepers are renewed, the annual expense is estimated at £20 to £25 per mile of track [£12 to £16 per km of track], and the figure given is 2 per cent. of the first cost. In the single phase system the catenary and trolley wires will require occasional renewal, whilst the gantries will require periodical painting and overhauling. The expense involved, together with that of inspection, replacement of broken insulators, track bonds, etc., is estimated at £30 to £40 per mile [£20 to £24 per km] per annum, and the figure given in the table is $2\frac{1}{2}$ per cent. of the first cost (£32 10*s*. per mile per annum) [£20 per km per annum].

The figure given for wages of drivers and assistants is an average figure derived from steam operation. It is subject to the correction of those in a better position than the writer to estimate on the matter, but is inserted here provisionally for the sake of completeness. It is obtained as follows: The Board of Trade Returns give figures for wages in connection with the working of locomotive engines for a number of the chief railways of the country. In 1905 this expense amounted to 3,78 pence per train mile [2,35 pence per train km]. This, however, includes not only wages of drivers and firemen, but also of cleaners, coal handlers, etc. The proportion of the total which is paid to drivers and firemen is taken the same as quoted in the late Mr. Langdon's paper "On the supersession of the steam by the electric locomotive,"[1] leading to the figure given.

The interest on the extra capital needed for electrification is taken at the rate of $3\frac{3}{4}$ per cent. per annum, which appears to be approximately the value of money invested in British railway securities.

The results of the calculations as derived from the constants in

[1] Journ. I.E.E., vol. xxx., p. 139.

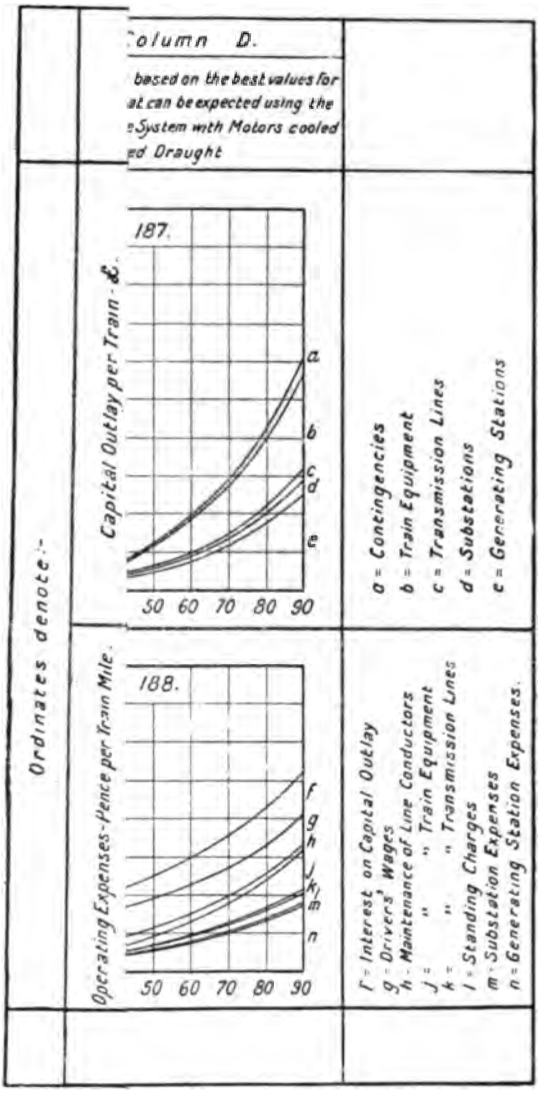
the above tables are embodied in the curves of Figs. 181 to 188. In Figs. 181 A to 188 A, the curves of Figs. 181 to 188 have been replotted in metric measure. Figs. 181 and 182 show respectively the capital outlay and operating expense for the constants in the columns marked A in the tables, being segregated to show how the total is built up. Figs. 183 and 184 stand in the same relation to the columns marked B; Figs. 185 and 186 to those marked C, and Figs. 187 and 188 to those marked D. The curves of capital outlay include only the items that can be expressed "per train," that is, they do not include line conductors where cost is naturally expressed "per mile" [kilometer], and is given in Table XCIII.

In order to show exactly how the curves have been derived, a calculation for a particular point will here be given. The constants will be taken from column A, and the free running speed on level track will be assumed at 75 miles per hour.

The mean train resistance, namely, that at 60 m ph (0,8 of 75 m ph) as given by formula 1, is 17,3 lb per ton, or 4330 lb for the 250 ton train. To this must be added 4 lb per ton of equipment weight. A simple equation for the latter quantity is obtained by equating the loss in the motors expressed as 8 per cent. of the input (derived from formula 3 and the motor efficiency) to the loss expressed in watts as 600 times the equipment weight. This gives, in the present case, an equipment weight of 117,5 tons. The total mean train resistance is, therefore, $4330 + 470 = 4800$ lb, and the output of the motors, given by formula 3, is 14 720 w hr per train mile. Dividing this by the equipment efficiency of 84 per cent., the input measured at the train is 17 530 w hr per train mile. Dividing again by the transmission efficiency (78 per cent.) the energy output of the generating station is 22 500 w hr per train mile. The scheduled speed being 0,7 of the free running speed, the average power output of the generating station is $(0,7 \times 75 \times 22,5)$ 1180 kw per train in service. Taking account of the number of trains in service at times of maximum load, as compared with the total number, the amount of standby plant, and the power used in the generating station itself, we obtain for the capacity of the generating plant, $\dfrac{1180 \times 0,625}{0,7 \times 0,94} = 1121$ kw per train. The train resistance at the free running speed of 75 ml ph, as given by formula 2, is 6470 lb. The power required for free running is therefore $6470 \times 75 \div 375 = 1294$ hp.

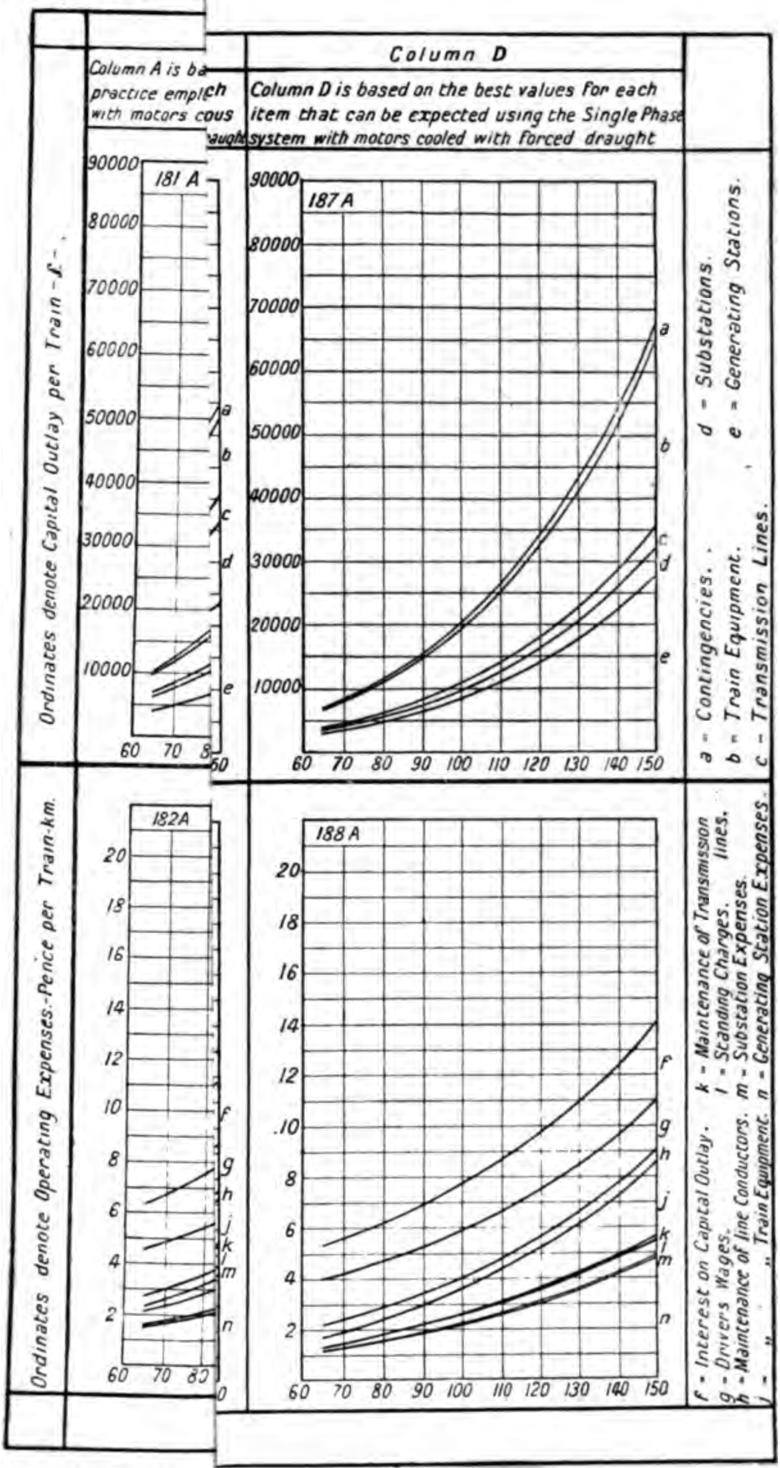
The average distance covered by each train in the course

PLAT



Figs. 181 RAILWAY SYSTEMS OF COLUMNS A, B,

[To face p. 300.



Figs. 181A—188A. ...F COLUMNS A, B, C, AND ... 3, AND 94.

of a year is 0,7 × 75 × 0,35 × 0,625 × 24 × 365 = 100 500 miles.

The capital costs per train are, therefore, as follows:—

	£
Generating station complete 1121 kw at £18 per kw	20 180
Sub-stations complete 1121 kw at £10 per kw	11 210
Transmission lines, 1121 kw at £3 per kw	3360
Train equipments, 117,5 tons at £120 per ton	14 100
Contingencies, 5 per cent. of the sum above	5440
Total capital outlay per train	£51 290

Capital outlay on line conductors per mile of single track (Table XCIII.) £1200

The operating expenses per train mile are as follows:—

	Pence
Generating costs, 22,5 units at 0,275*d.* per unit	6,19
Sub-station expenses, 22,5 units at 0,025*d.* per unit	0,56
Standing charges, 22,5 units at 0,094*d.* per unit	2,12
Maintenance transmission lines, 22,5 units at 0,006*d.* per unit	0,13
Maintenance train equipments 1294 hp at 0,00125*d.* per hp	1,62
Maintenance line conductors, £24 per 10 400 miles	0,55
Wages of drivers and assistants	2,99
Interest at 3¾ per cent. on £51 290, 100 500 ml per annum	4,59
Interest at 3¾ per cent. on £1200, 10 400 ml per annum	1,04
Total operating expense per train mile	19,79

The chief object that Mr. Carter had in view in carrying out this investigation was to show how electrical operation compared with steam for main line service. Mr. Carter points out that the actual comparison must, however, be left to those in a position to form an estimate of the costs of steam operation for this class of service. The railway companies' returns give average figures including goods and passenger, local, main and branch line service, but do not separate the results and show what would be the cost for such trains and such service as are discussed in this thesis. Mr. Carter states that since he is not in a position to ascertain what these costs would be, he accordingly leaves the subject at this point.

Sprague, in a recent paper entitled "Some Facts and Problems bearing on Electric Trunk Line Operation," states, "The continuous current and the three phase motors each have a continuous rate of energy input, while the single phase motor has an intermittent and variable rate. Moreover there is combined in the single phase motor two distinct functions, those of a motor and of a transformer, and the latter cannot be entirely eliminated. The result is a reduction in both normal and overload capacities. It is in this particular that the single phase motor, despite a great amount of experimental development, has remained defective; and while not prohibitive to the extent of making it an unworkable machine, its defects are so inherent as to place it at a serious disadvantage in individual comparisons with other types of motors. To attain the pre-eminence hoped for, the external advantages in current supply must be very marked. In fact, rated in the same manner and under like physical conditions, it is only about half as good as the continuous current motor. Or to put it another way, the weight of the complete single phase electrical equipment on a car or locomotive, including transformers, motors and controlling apparatus, for continuous hard service, and with like physical limitations and ventilation, is about twice that required for continuous current apparatus. In addition to this there is, of course, a material increase in the mechanical equipment necessary to carry the electrical apparatus. The reason is simple—it is because of the heat generated on account of lower electrical efficiency, and of working the fields of the motors at a reduced magnetic flux."

Sprague concludes his paper with the following statement: "No one can deny that if the single phase motor be developed to a high state of weight efficiency, unhandicapped by excessive weight of the collateral apparatus necessary on a car to utilize it, and if the capacity of conductors, especially steel conductors, for alternating currents can by any discovery be raised, the elimination of moving machinery in, and the simplification of sub-stations would open up a very extended and important field for the use of this type of apparatus. It seems to me that the present principal hope of usefulness of the single phase system is on roads of considerable extent which operate an irregular and sparse traffic, and where only a moderately expensive, or what may be called a second class overhead construction which will keep down the ratio of line investment to that of the balance of equipment, is tolerable. As one departs from this

condition, adopts more permanent construction, and faces the problems of denser traffics and higher capacities, the advantages of the single phase system will disappear, and the superiority of the continuous current equipment, with such improvements as are in sight, will become manifest. But whatever may be the future of single phase operation under the conditions stated, any present claim for it as the preferable equipment for congested service demanding high schedules and great capacity is not worth a moment's thought, for in this field, at least, it cannot touch the continuous current system. I see no practical necessity to formulate conclusions by averaging conditions, and I cannot conceive the responsible officers of any

TABLE XCV.

Considerations affecting the Commercial Success of Electric Railway Undertakings.

Headway in Minutes.	Trains in Service per km of Double Track at Schedule Speeds stated at Top of each Column in km per hr.									Millions of Train km per Annum per km of Double Track on Basis of Running 20 hrs per Train per Day.	Millions of Seat km per Annum per km of Double Track with Seats per Train stated at Top of each Column.				
	15	25	40	50	65	80	100	130	160		100	200	300	400	500
1,0	8,0	4,8	3,0	2,4	1,84	1,5	1,2	0,92	0,75	0,342	34,2	68,4	102,7	136,8	171,0
1,5	6,0	3,2	2,0	1,6	1,23	1,0	0,80	0,615	0,50	0,228	22,8	45,6	68,5	91,2	114,0
2,0	4,0	2,4	1,5	1,2	0,92	0,75	0,60	0,46	0,375	0,187	18,7	37,4	56,1	74,8	93,5
2,5	3,5	1,92	1,2	0,96	0,74	0,60	0,48	0,37	0,30	0,137	13,7	27,4	41,1	54,8	68,5
3,0	3,0	1,60	1,00	0,80	0,62	0,50	0,40	0,31	0,25	0,114	11,4	22,8	34,2	45,6	57,0
4,0	2,0	1,20	0,75	0,60	0,46	0,375	0,30	0,23	0,187	0,086	8,6	17,2	25,8	34,4	43,0
5,0	1,75	0,96	0,60	0,48	0,37	0,30	0,24	0,185	0,15	0,068	6,8	13,6	20,4	27,2	34,0
6,0	1,5	0,80	0,50	0,40	0,31	0,25	0,20	0,155	0,125	0,057	5,7	11,4	17,1	22,8	28,5
8,0	1,0	0,60	0,375	0,30	0,23	0,187	0,15	0,115	0,093	0,043	4,3	8,6	12,9	17,2	21,5
10,0	0,87	0,48	0,30	0,24	0,185	0,15	0,12	0,092	0,075	0,034	3,4	6,8	10,2	13,6	17,0
15,0	0,58	0,32	0,20	0,16	0,124	0,10	0,08	0,062	0,05	0,023	2,3	4,6	6,9	9,2	11,5

trunk line road being guided in their determination of what seems best for their own requirements, by consideration of what some road thousands of miles removed in location and enormously removed in operating conditions may do."

In selecting the lines along which to work in improving the net earning capacity of a railway, while we must make every effort to employ the most appropriate systems and equipments, we must not overlook the fact that there are other conditions essential to success which, although they are altogether independent of these engineering considerations, must be taken carefully into account by the engineer. Heavy capital outlay has already been incurred by all

large railways, and provision for interest and depreciation on this outlay will constitute one of the largest items for which provision must be made from the earnings. It is important to make every effort to increase the millions of seat kilometers per annum per kilometer of route. This is a function of the headway between

TABLE XCVI.

Considerations affecting the Commercial Success of Electric Railway Undertakings.

Millions of Seat Kilometers.	Train Load Factor, Average Percentage of Seats Occupied.	Millions of Passenger Kilometers.	Gross Receipts in Pounds (for Average Fare in Decimals of a Penny per Passenger km stated at Top of each Column).						Operating Expenses in Pounds (corresponding to Operating Expenses in Pence per 100 Seat km stated at Top of each Column)					
			0,35	0,40	0,45	0,50	0,55	0,60	1,0	1,5	2,0	2,5	3,0	3,5
	0,2	13	19 000	21 700	24 400	27 100	29 800	32 500						
65	0,3	19,5	28 400	32 500	36 600	40 600	44 700	48 700	2680	4060	5360	6700	8130	9400
	0,4	26	38 000	43 400	48 800	54 200	59 600	65 000						
	0,2	20	29 200	33 300	37 500	41 600	45 800	50 000						
100	0,3	30	43 750	50 000	56 250	62 500	68 800	75 000	4120	6250	8240	10 300	12 500	14 400
	0,4	40	58 400	66 600	75 000	83 200	91 600	100 000						
	0,2	26	38 000	43 400	48 800	54 200	59 600	65 000						
130	0,3	39	56 800	65 000	73 200	81 200	89 400	97 500	5360	8120	10 720	13 400	16 250	18 800
	C,4	52	76 000	86 800	97 600	108 400	119 200	130 000						
	C,2	32	46 700	53 400	60 000	66 600	73 400	80 000						
160	0,3	48	70 000	80 000	90 000	100 000	110 000	120 000	6600	10 000	13 350	16 680	20 000	23 [illegible]
	0,4	64	93 400	106 800	120 000	133 200	146 800	160 000						
	0,2	40	58 400	66 600	75 000	83 200	91 600	100 000						
200	0,3	60	87 500	100 000	112 500	125 000	137 500	150 000	8250	12 500	16 500	20 600	25 000	28 800
	0,4	80	116 800	133 200	150 000	166 400	183 200	200 000						
	0,2	46	67 200	76 800	86 400	96 000	105 500	115 000						
230	0,3	69	100 600	115 000	129 400	144 000	158 000	172 500	9500	14 400	19 000	23 800	28 800	33 200
	0,4	92	134 400	153 600	172 800	192 000	211 000	230 000						
	0,2	52	76 000	86 800	97 600	108 400	119 200	130 000						
260	0,3	78	113 600	130 000	146 400	162 400	178 800	195 000	10 720	16 250	21 440	26 800	32 500	37 [illegible]
	0,4	104	152 000	173 400	195 200	216 800	238 400	260 000						
	0,2	58	84 700	97 000	109 000	121 000	133 000	145 000						
290	0,3	87	127 000	145 000	163 000	181 000	199 000	217 500	12 000	18 150	24 000	30 000	36 300	42 000
	0,4	116	169 400	194 000	218 000	242 000	266 000	290 000						
	0,2	64	93 400	106 800	120 000	133 200	146 800	160 000						
320	0,3	96	140 000	160 000	180 000	200 000	220 000	240 000	13 200	20 000	26 700	33 360	40 000	46 700
	0,4	128	186 800	213 600	240 000	266 400	293 600	320 000						
	0,2	80	116 800	133 200	150 000	166 400	183 200	200 000						
400	0,3	120	175 000	200 000	225 000	250 000	275 000	300 000	16 500	25 000	33 000	41 600	50 000	58 400
	0,4	160	233 600	266 400	300 000	333 800	366 400	400 000						
	0,2	96	140 000	160 000	180 000	200 000	220 000	240 000						
480	0,3	144	210 000	240 000	270 000	300 000	330 000	360 000	20 000	30 000	40 000	50 000	60 000	70 000
	0,4	192	280 000	320 000	360 000	400 000	440 000	480 000						
	0,2	112	163 500	187 000	210 000	233 500	256 500	280 000						
560	0,3	168	245 000	280 000	315 000	350 000	385 000	420 000	23 300	35 000	46 600	58 400	70 000	81 600
	0,4	224	327 000	374 000	420 000	467 000	513 000	560 000						

All values stated are "per annum per kilometer of double track."

trains and the number of seats per train as shown in Table XCV. Hence we must provide long platforms at stations and trains designed for maximum seating capacity per meter length of train, and we must run with a minimum of headway between trains. Table XCV. also shows us that the millions of seat kilometers per

annum per kilometer of route is independent of the schedule speed. High schedule speed will, however, be an inducement to traffic, and will improve the train load factor, that is to say, the average percentage of the seats occupied during the entire year. The cost for power for obtaining moderately high schedule speeds is an insignificant item, and should not be a deterrent; but beyond a certain point, the seats per meter of length of train will be seriously limited by high schedule speeds, and this will be a factor in determining the speed consistent with maximum earnings. The fares should be adjusted to the value at which, with the train load factor, resulting from them, the gross receipts per kilometer of route are a maximum.

Some roads would be able to increase their earnings by lower fares in pence per kilometer, others by higher fares. The receipts corresponding to various schedules, train load factors and fares per passenger-kilometer are set forth in Table XCVI., in the last section of which are shown the running costs in pounds per kilometer of route, for various running costs ranging from 2,5*d.* to 5*d.* per hundred seat kilometers. In the examples worked out in this article the running costs were about 3*d.* per hundred seat kilometers.

An enterprising management, with an appreciation of the engineering elements involved, and always on the alert to introduce incentives to traffic, and thus to improve the train load factors for a given fare per passenger-kilometer, can, in the case of any given road, often exert a more marked effect in improving the earning capacity than can be accomplished by engineers.

APPENDIX

ABBREVIATIONS AND EQUIVALENT VALUES FOR UNITS OF ENERGY, POWER AND PRESSURE

TABLE XCVII.

Energy Units, with Abbreviations; and Corresponding Values expressed in Joules.[1]

Unit.	Abbreviation.	Value in Joules.
1 Kilowatt hour	1 kw hr	3 600 000
1 Kilogram calorie	1 kg cal	4190
1 Kilogram meter	1 kg m	9,81
1 Horse power hour	1 hp hr	2 680 000
1 British Thermal unit	1 B Th U	1055
1 Foot pound	1 ft lb	1,356

TABLE XCVIII.

Power Units, with Abbreviations; and Corresponding Values expressed in Watts.

Unit.	Abbreviation.	Value in Watts.
1 Kilowatt	1 kw	1000
1 Kilogram calorie per second	1 kg cal ps	4190
1 Kilogram meter per second	1 kg m ps	9,81
1 Horse power	1 hp	746
1 British Thermal unit per second	1 B Th U ps	1055
1 Foot pound per second	1 ft lb ps	1,356
1 Joule per second	1 joule ps	1,000

[1] The joule may be defined as 10^7 ergs, or as one watt second.

TABLE XCIX.

Equivalent Values for Energy expressed in different Units (English and

	Kw hr.	Kg cal.	Kg m.	Hp hr.	B Th U.	Ft lb.
1 kw hr is equal to	1	860	367 000	1,34	3411	2 559 000
1 kg cal ,, ,,	0,00116	1	427	0,001559	3,97	3081
1 kg m ,, ,,	0,00000272	0,00234	1	0,00000365	0,00930	7,23
1 hp hr ,, ,,	0,746	641	274 000	1	2545	1 980 000
1 B Th U ,, ,,	0,000293	0,252	107,6	0,000393	1	778
1 ft lb ,, ,,	0.000000377	0,000324	0,1382	0,000000505	0,001285	1
1 joule ,, ,,	0,000000278	0,0002385	0,1020	0,000000373	0,000948	0,738

TABLE C.

Equivalent Values for Power expressed in different Units (English and

	Kw.	Kg cal ps.	Kg m ps.	Hp.	B Th U ps.	Ft lb ps.
1 kw hr is equal to	1	0,238	102,0	1,34	0,947	737
1 kg cal ps ,, ,,	4,20	1	427	5,61	3,97	3088
1 kg m ps ,, ,,	0,00981	0,00234	1	0,00315	0,00930	7,23
1 hp ,, ,,	0,746	0,1781	76,0	1	0,707	550
1 B Th U ps ,, ,,	1,055	0,252	107,6	,415	1	778
1 ft lb ps ,, ,,	0,001356	0,000324	0,1383	0,001818	0,001285	1
1 joule ps ,, ,,	0,001	0,0002385	0,1020	0,001242	0,000948	0,738

TABLE CI.

Pressures.

	Lb p sq in.	Kg p sq cm.	Inches of Mercury.	Mm of Merc
1 lb p sq in . .	1	0,0703	2,036	51,71
1 kg p sq mm .	14,22	1	28,96	735,5
1 in of mercury .	0,4912	0,0345	1	25,4
1 mm of mercury .	0,0193	0,00136	0,03937	1

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[BY E. S. W.]

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